38-KHZ ADCP INVESTIGATION OF DEEP SCATTERING LAYERS

IN SPERM WHALE HABITAT IN THE NORTHERN GULF OF MEXICO

A Thesis

by

AMANDA MAY KALTENBERG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Oceanography

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Approved as to style and content by:

Douglas C. Biggs (Co-Chair of Committee)	Steven F. DiMarco (Co-Chair of Committee)
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ABSTRACT

38-khz ADCP Investigation of Deep Scattering Layers

in Sperm Whale Habitat in the Northern Gulf of Mexico. (December 2004)

Amanda May Olson, B.S., University of North Dakota

Co-Chairs of Advisory Committee: Dr. Douglas C. Biggs
Dr. Steven F. DiMarco

A hull-mounted 38-kHz phased-array acoustic Doppler current profiler (ADCP) was used to acoustically survey the continental margin of the northern Gulf of Mexico (GOM) during 6 cruises in 2002-2003. This is the first backscatter survey with a 38-kHz ADCP in the Gulf of Mexico. ADCPs have been used as a proxy to measure the volume backscatter return from plankton in the water column, however previous studies were restricted to the upper 200 to 300 meters due to the relatively high frequency of operation (150-300 kHz) of the transducers. In addition to measuring deep water current velocities, the 38-kHz phased-array ADCP can measure Relative Acoustic Backscatter Intensity (RABI) as deep as 1000 meters. The daytime depth of the main deep scattering layer at 400 to 500 meters was resolved, and locally high backscatter intensity can be seen down to 800 meters. The objectives were to determine how to analyze RABI from the instrument to resolve scattering layers, and then to seek secondary deep scattering layers of potential prey species below the main deep scattering layer, from 600 to 800 meters in the feeding range for Gulf of Mexico sperm whales.

Based on RABI from the 38-kHz ADCP, secondary DSLs in sperm whale diving range were more commonly recorded over the continental shelf than in the deep basin region of the Gulf of Mexico. The daytime depths of migrating plankton showed variation depending on physical circulation features (cyclone, anticyclone, proximity to Mississippi river, and Loop Current) present. Vertical migrations compared between concurrently running 38 and 153-kHz ADCPs showed an overlap of acoustic scatterers recorded by the two instruments, however the 153-kHz instrument has much finer vertical resolution. Vertical migration rates were calculated and simultaneous net tow samples from one of the cruises was used to compare abundance estimates by the two methods.

ACKNOWLEDGMENTS

Funding for this project was provided by the Minerals Management Service (MMS) contract No. 1435-01-02-CA-85186, from 2002 to 2004. I presented results from this research at the AGU Ocean Sciences Meeting held in Portland, OR in January, 2004. Funding for this presentation came from the Oceanography Graduate Council and the Office of Graduate Studies.

I would like to thank the co-chairs of my thesis committee, Dr. Doug Biggs and Dr. Steve DiMarco, for their academic and research guidance throughout my time at Texas A&M. I'd also like to thank my committee members, Dr. John Wormuth and Dr. Markus Horning. I've learned so much from each one of my committee members.

I'd like to thank TAMU marine Ops, Eddy Webb and Paul Clark, for collecting ADCP data for me, and Matt Howard, Norman Guinasso, and Ann Jochens for providing me with copies of cruise data as I needed them.

Dr. Mark Johnson from Woods Hole Oceanographic Institute provided sperm whale diving data that I've included in the thesis. Dr. Robert Leben from Colorado Center of Astrodynamics Research provided online data of sea surface height fields from satellite altimetry that are also used in this thesis.

I'd like to thank all the professors I had for courses, the staff, and the graduate students from the TAMU Oceanography Department for sharing their wisdom and support while I've been here, and for making this degree a fun and rewarding experience.

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CHAPTER I

INTRODUCTION

The spatial and temporal distribution of organisms in the open ocean can be highly variable because of biological, physical, and chemical interactions that determine population change and movements of individuals. Methods for studying these pelagic community dynamics are continually improving with technology, so researchers must seek ways to study them in ever-greater detail as well as to study environments that were previously inaccessible. In this study, a relatively new acoustic instrument, the 38-kHz phased-array acoustic Doppler current profiler (ADCP), was used to resolve the acoustic signature of deepwater prey communities down to 1000 meters. These communities were too deep to study using 153 and 300-kHz hull-mounted ADCPs, which had a vertical range of 300 and 100 meters respectively. This research reports the first acoustic backscatter survey of the Gulf of Mexico with a 38-kHz ADCP.

In this pilot study for 38-kHz ADCP backscatter, I will describe the methods used to analyze data from the instrument. In addition to this description, I will examine some of the biological and physical factors that may influence organisms that make up one particular deepwater marine community, the deep scattering layer of the northern Gulf of Mexico region. In this thesis, I define a deep scattering layer (DSL) as a horizontal aggregation of pelagic organisms that, when acoustically surveyed, produces an anomalous high intensity return from the water column. DSLs likely have an

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This thesis follows the style and format of Deep-Sea Research I.

important role in biological interactions in the Gulf of Mexico (GOM), in particular with sperm whales *(Physeter macrocephalus)* and their squid prey. Sperm whale distributions have previously been nearly impossible to correlate directly with the distributions of their prey (Jaquet and Gendron, 2002). With the 38-kHz ADCP, distributions of prey scattering layers present in sperm whale foraging depth range are surveyed. I will present results of a survey of these deep scattering layers, which are more directly related to sperm whales than distributions of plankton as in previous ADCP surveys of sperm whale habitats.

Early use of acoustics in oceanography employed relatively low frequency echosounders (10-40 kHz) aboard ships for continuous measurements of water depth and for studies of the surface features of the seafloor (Duvall and Christiansen, 1946; Herring, 2002). Unexpected layers of sound scattering were encountered in midwater at a couple hundred meters below the surface that ascended to the surface at dusk and descended near dawn, and which separated into different layers. These were later recognized as deep scattering layers (DSLs) of biological organisms (Johnson, 1977). Through subsequent studies on DSLs, we now know that individual organisms undergo daily migrations out of the surface waters to avoid predators during the daylight hours, and to feed near the surface at nighttime (Hays, 2003). Known as diel vertical migration (DVM), this behavior is a universal feature in all the world's oceans. In Chapter III of this thesis, DVM will be further discussed as well as the main DSL at about 500 meters, including calculations of the vertical migration rates and timings observed for the organisms of the target size range. Regional variability of the intensity and depths of the DSL are related to physical and geographic variability.

ADCPs

ADCPs primarily use sound which is scattered by biological particles in the water to measure current vectors in the water column. The backscattered acoustic signal can also serve as a proxy for the scattering organisms distribution and abundance. In acoustic backscatter surveys, a source sound, 'ping', is transmitted from an ADCP transducer and propagated through the water column. In theory, a particle can reflect sound of wavelengths shorter than its body length. The strength of the reflected signal received back at the transducer is recorded by the ADCP and can then be used for relative biomass estimates.

Several previous studies have used ADCP backscatter to estimate the volume of zooplankton and micronekton (Brierley et al., 1998; Ressler, 2001). 'Sea truthing' of ADCPs have been accomplished in combination with net trawls to compare volume biomass by the two methods collected simultaneously (Greene et al., 1998; Ressler, 2001). Species specific scattering behaviors have shown that the composition and orientation of the targets lead to variability in backscatter returns (Stanton et al., 1994; McGehee et al., 1998; Benoit-Bird and Au, 2002). ADCPs have also been used in combination with other instruments such as the multifrequency EK500 echosounder and the towed environmental sensor, SeaSoar, to get more detailed information of the environment (Griffiths and Diaz, 1996; Roe et al., 1996).

In addition to describing the abilities and limitations of the instruments used in these previous ADCPs studies, some researchers have also used the data from the ADCP to analytically study oceanic communities (Heywood et al., 1991; Zimmerman & Biggs, 1999; Ressler, 2002; Zedel et al., 2003). In Chapter IV, I will investigate the distribution of a secondary DSL, a scattering layer below the main DSL and found between 600 and 800 meters below surface. This scattering layer is of special interest because it appears to be a potential prey source for deep water predators like deep-diving sperm whales. This secondary DSL likely represents an important trophic link between plankton and the squid on which sperm whales forage.

Physical environment of the Gulf of Mexico

The Gulf of Mexico is a semi-enclosed, sub-tropical basin. The near-surface circulation is dominated by the Loop Current (LC), which is formed when warm Caribbean water enters through the Yucatan Channel and leaves through the Florida Straights (Figure 1). The size and range of the Loop Current are highly variable, the northward penetration can range from 23°N to 29°N. Clockwise rotating anticyclonic eddies (200-400km) are periodically shed off from the LC (Sturges and Leben, 2000). These eddies can migrate over tens to hundreds of kilometers westward, where they eventually dissipate, lasting up to six months and more (Nowlin et al., 2000). Smaller mesoscale cyclonic eddies (50-150km) are occasionally found over the middle continental slope with anticyclonic LC eddies through interactions with topography or other eddies. These eddies, both cyclonic and anticyclonic, play a major role in

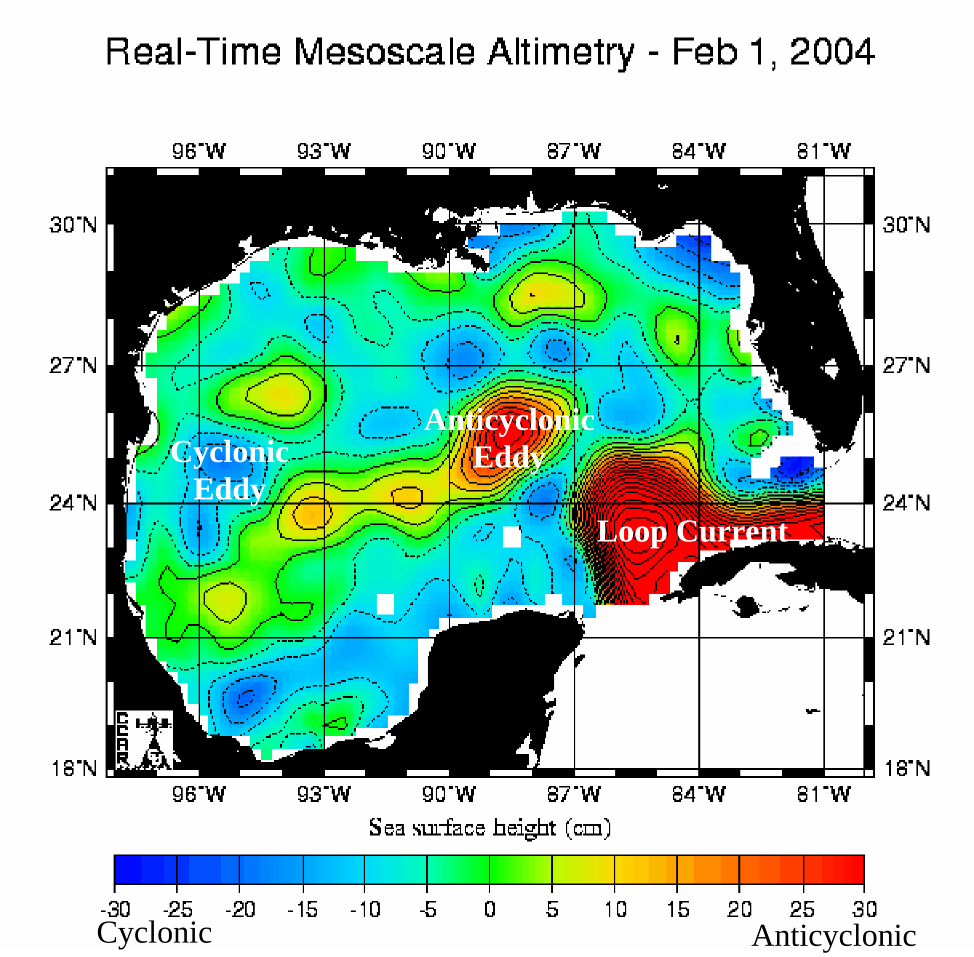


Figure 1. Gulf of Mexico mesoscale circulation features include the Loop Current, which enters the Gulf of Mexico basin through the Yucatan Channel and exits through the Florida Straits, anticyclonic Loop Current eddies, and counter-rotating cyclonic eddies. Figure courtesy of R. Leben, University of Colorado Center for Astrodynamic Research (http://ccar.colorado.edu/~realtime/gsfc_gom-real-time_ssh/).

physical dynamics of the Gulf of Mexico and contribute to the forcing of biological processes. Cyclonic eddies produce doming of deep, colder water, which is upwelled towards the surface, carrying deep water nutrients to the photic zone (<100m). The nutrient-rich cyclones support higher stocks of primary production and zooplankton, and are temporary 'oases' of biological productivity in the otherwise oligotrophic adjacent water (Biggs, 1992; Biggs and Ressler, 2001). These oases of productivity attract predators and are seen as biological hotspots.

The Gulf of Mexico contains several different water masses, as detected by combined temperature-salinity and chemical concentration profiles (Morrison et al., 1983, see Table 1). The Subtropical Underwater ranges from 0 to 250 meters depth from the surface. Temperature from the surface to the upper thermocline (upper 250m) ranges from about 30°C to 10°C with a salinity range of 36.5 to 35.5, except near coastal sources of terrestrial freshwater inputs. Tropical Atlantic Central Water (TACW) ranges from 250 to 400 meters depth and temperatures between 10 and 8°C. Antarctic Intermediate Water (AAIW) ranges from 500 to 700 meters and temperatures of 7 to 5°C. This vertical structure of water masses is an important physical characteristic to consider when studying DVM dynamics. Vertically migrating organisms pass through hundreds of meters of the water column, traversing a wide range of environments and several water masses. Organisms of the main DSL have daytime depths near 500 meters in AAIW where temperatures are between 7 and 5°C. DVM organisms then ascend into the upper 100 meters in the surface mixed layer at nighttime, where temperature may range up to 30°C and vary seasonally. Thus, these vertically migrating animals must be

Table 1
Water property extrema in the Western Gulf of Mexico and the associated water masses and potential density surfaces

Water Mass	Extremum	Concentra-tions	mg cm^{-3}	Depth range (m)
Subtropical Underwater	salinity maximum	36.4-36.5%	25.4	0-250
Tropical Atlantic Central Water	oxygen minimum	2.5-2.9 ml/l	27.15	250-400
Antarctic Intermediate Water	nitrate maximum	29-35 ug-at/l	27.3	500-700
Antarctic Intermediate Water	phosphate maximum	1.7-2.5 ug-at/l	27.4	600-800
Antarctic Intermediate Water	salinity minimum	34.88-34.89%	27.5	700-800
Mixture of upper North Atlantic Deep Water and Caribbean	silicate maximum	24-28 ug-at/l	27.7	1000-1100

From Morrison et al., (1983).

able to tolerate temperature fluctuations of about 25°C daily. However, as I will show in Chapter IV, sperm whales feed by day as well as by night on non-migratory prey that remain within the depth range of AAIW. Since these animals are non-migratory, they remain in constant environmental conditions.

Overview of this study

Data for this thesis were collected from two different large studies funded by the Department of the Interior, Mineral Management Service, the Deep Gulf of Mexico Benthic Study (DGoMB), and the Sperm Whale Seismic Study (SWSS) (see Table 2 for cruise summaries). DGoMB was a three-year field study from 2000 to 2002, in the northern and central Gulf of Mexico and focused on benthic ecology. DGoMB repetitively occupied 66 hydrographic stations in the northern shelf, slope, and deep basin regions and routinely collected shipboard ADCP data while underway. SWSS was a three-year field study from 2002 to 2004 that targeted the northern slope region of the Gulf of Mexico along the 1000 m isobath and focused on sperm whale ecology and their response to seismic survey noise. Because the data of this thesis are from both programs, I have had access to both temporal and spatial variability. This has allowed for a comparison of in relative backscatter between slope and abyssal plain water depths.

The three main objectives for this thesis are:

Objective 1: Develop a method to analyze relative backscatter data from the 38-kHz phased-array ADCP.

Table 2
Cruise dates, data types, geographic regions, and features present for data analyzed in this thesis

Cruise	**Dates**	**Data Analyzed**	**Gulf of Mexico Region**	**Hydrographic Features Present**
SWSS S-tag 02G08	June 20 - July 8, 2002	38 kHz ADCP	northern	slope, eddies
SWSS D-tag 02G11	August 19 - September 15, 2002	38 kHz ADCP	northern	eddies, Mississippi River plume
SWSS Habitat 03G06	May 31- June 21, 2003	38 kHz ADCP, trawl sampling	northern	eddies, Mississippi River plume
SWSS S-tag 03G07	June 26 - July 16, 2003	38 kHz ADCP	northern	slope, eddies
DGoMB 4A 02G07	June 1- June 14, 2002	38, 153 kHz ADCP	central	central Loop Current
DGoMB 4B 02G10	August 2 - August 13, 2002	38, 153 kHz ADCP	central	central Loop Current

Objective 2: Characterize the main scattering layer (DSL) and its daytime depth and backscattering intensity in various hydrographic regimes.

Objective 3: Characterize scattering layers below the main DSL and attempt to correlate prey layers with sperm whale diving depths.

Based on these objectives, the following hypotheses are tested:

H1: The depths and intensities for relative acoustic backscatter of the main DSL are related to hydrographic and geographic regions.

H2: ADCP backscatter shows higher abundance of potential prey scatterers in deep scattering layers in regions where sperm whale predators are abundant.

H3: The occurrence of a strong mesoscale anticyclone eddy and the absence of sperm whales feeding in that area coincides with an absence of secondary deep scattering layers (>600m).

The general locations of the acoustic, biological, physical, and chemical data collected during SWSS and DGoMB are shown in Figure 2. 38-kHz ADCP data were collected from 6 cruises between 2002 and 2003 (see Table 2). Although ADCP data were collected during all 6 different cruises, much of the analysis focused on specific days. Vertical migrations were taken from representative sections of ADCP data based on data quality. In addition to the 38-kHz ADCP data, other sources of data used in this analysis includes; backscatter data from a 153-kHz broadband ADCP, IKMT net trawl sampling, TOPEX/ERS satellite sea surface height field, sperm whale diving profiles, flow-through sea surface temperature, salinity, and fluorescence, and CTD optical backscatter and fluorescence.

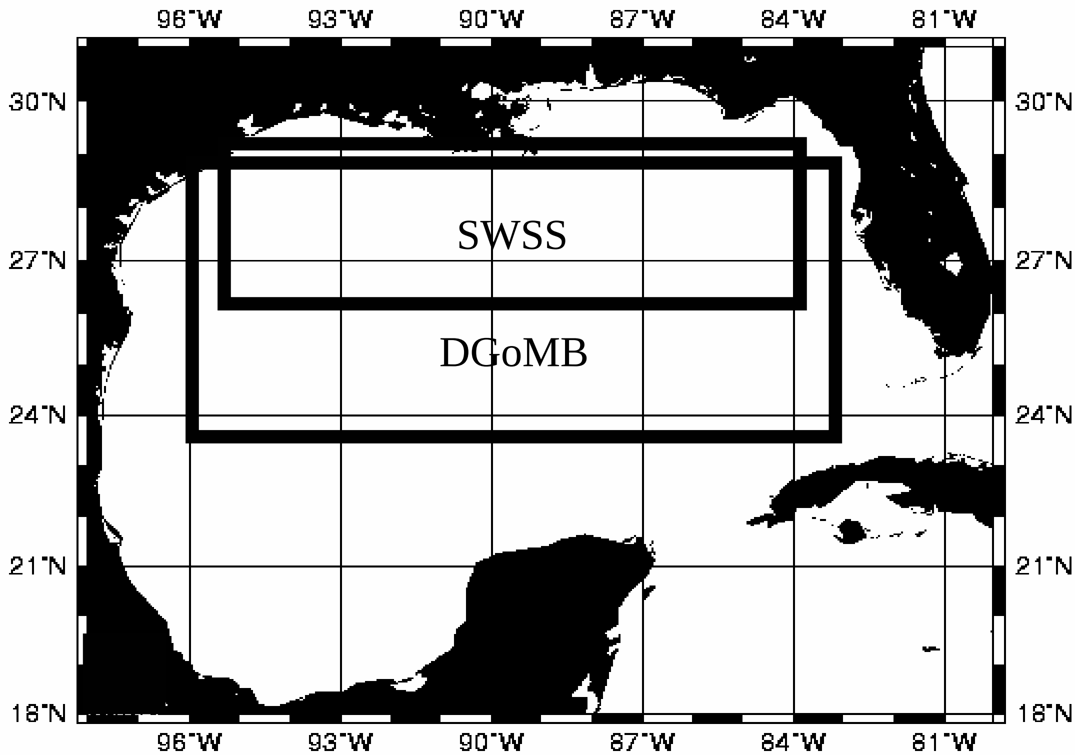


Figure 2. The study area for this thesis includes the northern Gulf of Mexico slope and deep basin regions. This thesis includes data collected on cruises onboard the *R/V Gyre* during the SWSS and DGoMB programs.

The 38-kHz ADCP measures relative acoustic backscatter intensity (RABI), which is the signal of the sound received back at the transducer after being transmitted from the instrument and scattered off a particle in the water column. The 38-kHz ADCP used in this study usually receives valid RABI above the background level to a depth range between 800 to 1000 meters. However, several different factors may decrease this depth range by masking the signal with high background noise. These are explained further in Chapter II. Beam-agreement among the four beams was found to be a good indicator of the quality of backscatter signal to noise, so it was used to identify and eliminate poor signal. All signal data with beam-agreement less than 200 (80%) were considered poor signal to noise and deleted from the analysis. Beam-agreement was usually high enough in the upper half of the record to resolve the daily migrations, however, below the main DSL data quality varied with ship speed.

CHAPTER II

ACOUSTIC BACKSCATTER SURVEYING WITH THE 38-KHZ ADCP

Introduction

Acoustic methods are becoming a widely useful and popular approach to oceanographic studies (Greene et al., 1998). Although ADCPs were originally developed to study current velocities with depth in the oceans, they are becoming increasingly used to measure backscatter strength of the reflected signal from scattering organisms in the water column. Since the strength of the return signal is proportional to the volume of scattering organisms in that bin, backscatter signal is used to construct vertical distributions of plankton. Testings for the reliability of ADCPs to measure plankton distributions have shown that the backscatter signal is positively correlated with plankton standing stocks (Stanton et al., 1994; Brierley et al., 1998).

ADCPs of higher frequencies (153 and 300 kHz) have multipiston transducers. Each one of four transducers emits a ping simultaneously, creating 4 separate acoustic beams. The 38-kHz ADCP has a very different, single phased-array transducer. The phased-array transducer is composed of an array of elements that emit sound simultaneously (R.D. Instruments, 1996). A pattern in the sound emissions is specified for phase legs to allow for organized interference to result in the formation of four separate acoustic beams. The advantage of the phased-array transducer over the multipiston type is that it can be fabricated much smaller in overall geometric size yet still produce separate acoustic beams. This is an important benefit for the lower frequency ADCPs, since previously these required one meter in diameter or larger transducers. There are two modes of ADCP signal collection, broadband and narrowband. The 38-kHz ADCP used for this study is a broadband type. Broadband instruments record data of higher resolution, and less sampling time is required to resolve the signal pattern than for narrowband instruments.

Backscatter signal strength has traditionally been converted to volume backscatter intensity (VBI) in units of decibels (Sv) for biomass estimates from broadband multi-piston ADCPs (Deines, 1999). The broadband 38-kHz phased-array ADCP is used to record relative acoustic backscatter intensity (RABI) from organisms. RABI is used instead of VBI because the characteristics of the acoustic beam for the phased-array type transducer are not known at this time and, according to the manufacturer, R.D. Instruments, may be quite different than the multi-piston acoustic beam. Therefore, losses to the return signal due to beam spreading and sound absorption are unknown and must be experimentally determined before data can be converted to VBI. However, since the same 38-kHz instrument was used for all cruises investigated here, we are confident to make valid quantitative assertions between backscatter at similar depths and when comparing different cruises.

Results of data analysis

ADCPs measure the Doppler shift of a reflected sound to calculate the velocity vector of a current (R.D. Instruments, 1996). Current velocity vectors are obtained when the transmitted sound is reflected from organisms in the water column. Long range profiling of currents have previously been measured with a 38-kHz ADCP (Edelhauser et al., 1999). Figure 3 shows an example of the surface current vectors obtained with the 38-kHz ADCP in this study. Here, current vectors for this cruise are superimposed on a sea surface height field that has been optimally interpolated from satellite altimetry data (DiMarco et al., 2003). Both the data from the current velocity vectors and the sea surface height show a large clock-wise rotating Loop Current eddy in the study area at the time of the cruise.

Backscatter data from the 38-kHz ADCP were collected in 16 meter vertical bins over 5 minute ensembles for each of the four acoustic beams orientated at 30 degrees from the transducer. Generally, there should be higher return signal when there are more, or larger, scatters in the bin reflecting sound. The cruise-long average ensemble profile for two different cruises, one from the slope region from SWSS and one from the deep basin region from DGoMB, is shown in Figure 4. Average profiles show a high intensity layer at the surface with generally decreasing signal with depth. High intensity peaks were observed in all profiles at about 500 m due to the main deep scattering layer of pelagic organisms. Because diel vertical migrations of organisms occur regularly, the daytime and nighttime signals apparently cancel each other out in this average vertical profile, so the broad peak between 400 to 600 m likely represents non-migrating scatterers. In some, but not all profiles, a secondary DSL was observed between 600 and 800 m depth from the surface. The difference in the presence of a secondary scattering layer from 600 to 800 m will be discussed further in Chapter IV.

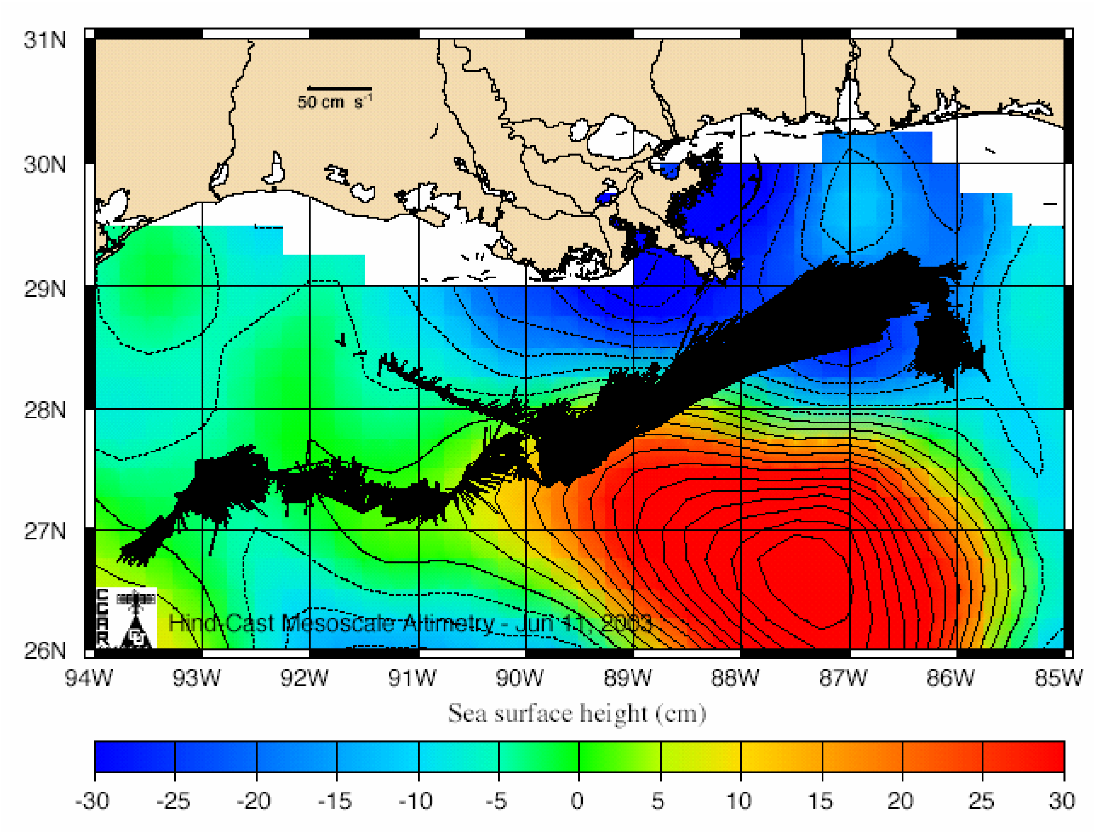


Figure 3. Surface current velocity vectors from the 38-kHz ADCP superimposed on sea surface height field for the SWSS03 Leg1 cruise, June, 2003. Velocity vectors were computed by Steve DiMarco (TAMU), SSH data are courtesy of R. Leben University of Colorado Center for Astrodynamics Research (available at: http://ccar.colorado.edu/~realtime/gsfc_gom-real-time_ssh/).

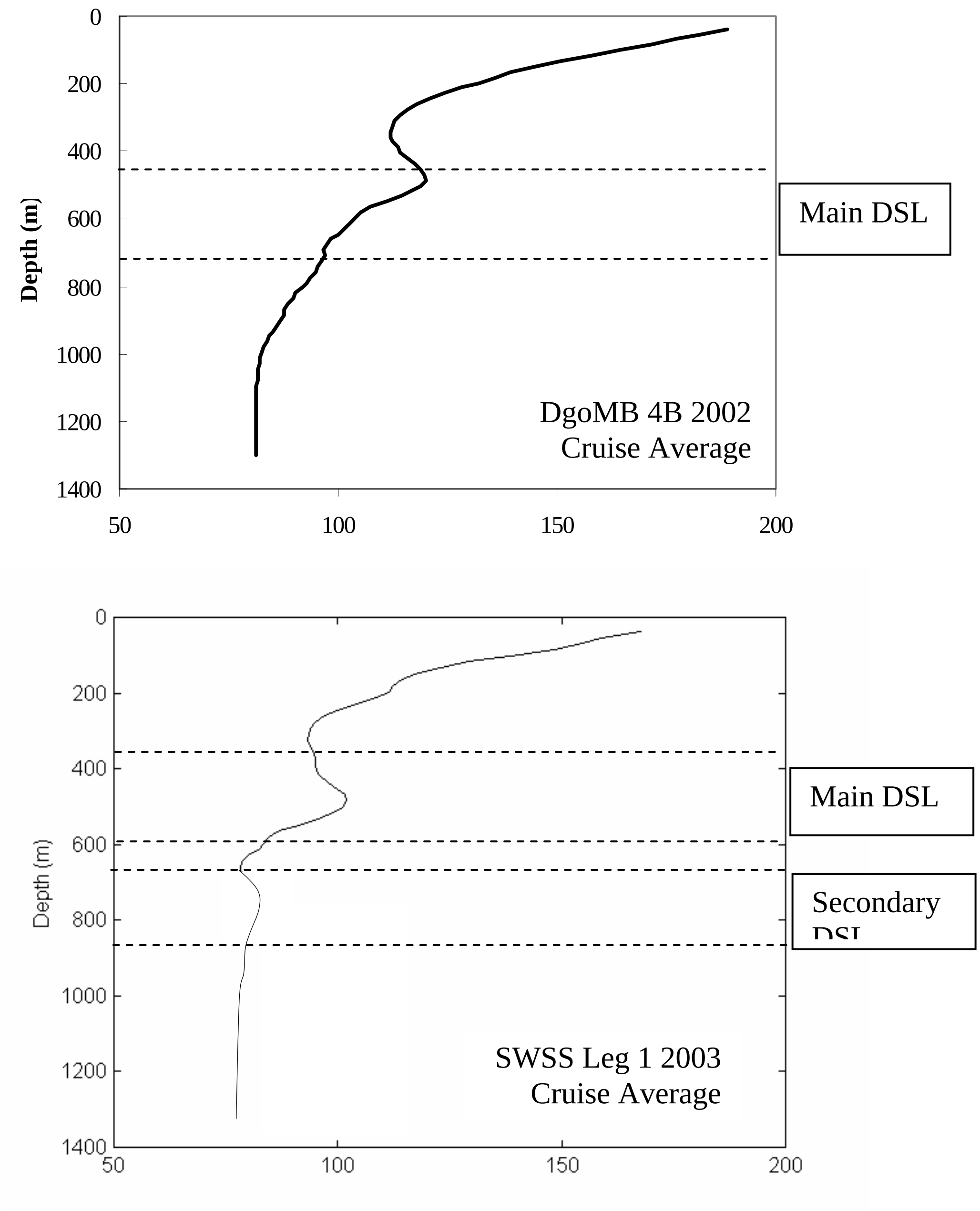


Figure 4. The average profile from all ensembles over the entire cruise for a DGoMB cruise (top panel), and for a SWSS cruise (lower panel). A broad zone of deep scattering is evident between 400 to 600 meters during DGoMB and SWSS, and a secondary scattering layer between 600 to 800 meters during SWSS.

Backscatter data quality was variable and found to be a function of ship speed. Between-beam agreement was used as an indicator for data quality and a method for quality control (Figure 5). Ship speed has a direct effect on the quality of ADCP backscatter data, usually manifest as decreasing beam agreement with increasing speed. When the ship is moving at fast speeds, noise is high compared to the signal, so detail of the signal is masked. This is likely due to a turbulent noise produced when the ship is underway at high speeds because of the flow over the transducer causes friction of water with the transducer. As ship speeds increase farther, there may be air bubbles flowing across the transducer that could magnify the noise. For all analysis of 38-kHz ADCP backscatter, between-beam agreement (a correlation parameter measured by the instrument) of less than 80% (200 out of 250) was not included. The top panel of Figure 6 shows a WINADCP plot over one day with periods of low signal to noise that coincided with high ship speeds. The lower panel of Figure 6 shows the same 38-kHz ADCP backscatter plot after low beam agreement values were not included (shown in white).

The frequency of operation of an ADCP determines the minimum vertical bin resolution as well as the maximum vertical range. Higher frequencies can resolve data in smaller vertical bins, giving the user better resolution, but the maximum depth range of sound penetration will be shallower. Transmissions from low frequency ADCPs are able to penetrate deeper in the water column, but the trade off is with lower vertical resolution that results from larger depth bins. For example, an advantage of the 38-kHz ADCP over the 153-kHz ADCP is that the 38-kHz ADCP has a much larger

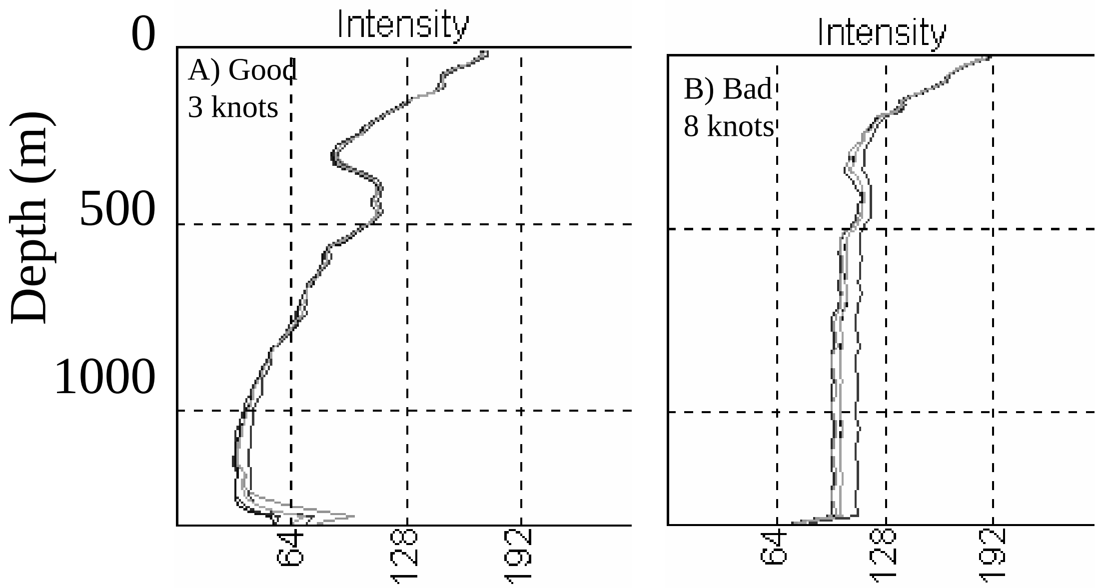


Figure 5. Example of beam-agreement comparison for slow and fast ship speed. At ship speed of 3 knots (A), beam agreement is high throughout water column until near 1,000 meters. When the ship is going 8 knots (B) beam-agreement is low over much more of the vertical range (beams separate at about 200 meters). Based on this, data with beam-agreement among the 4 beams less than 80% was not used.

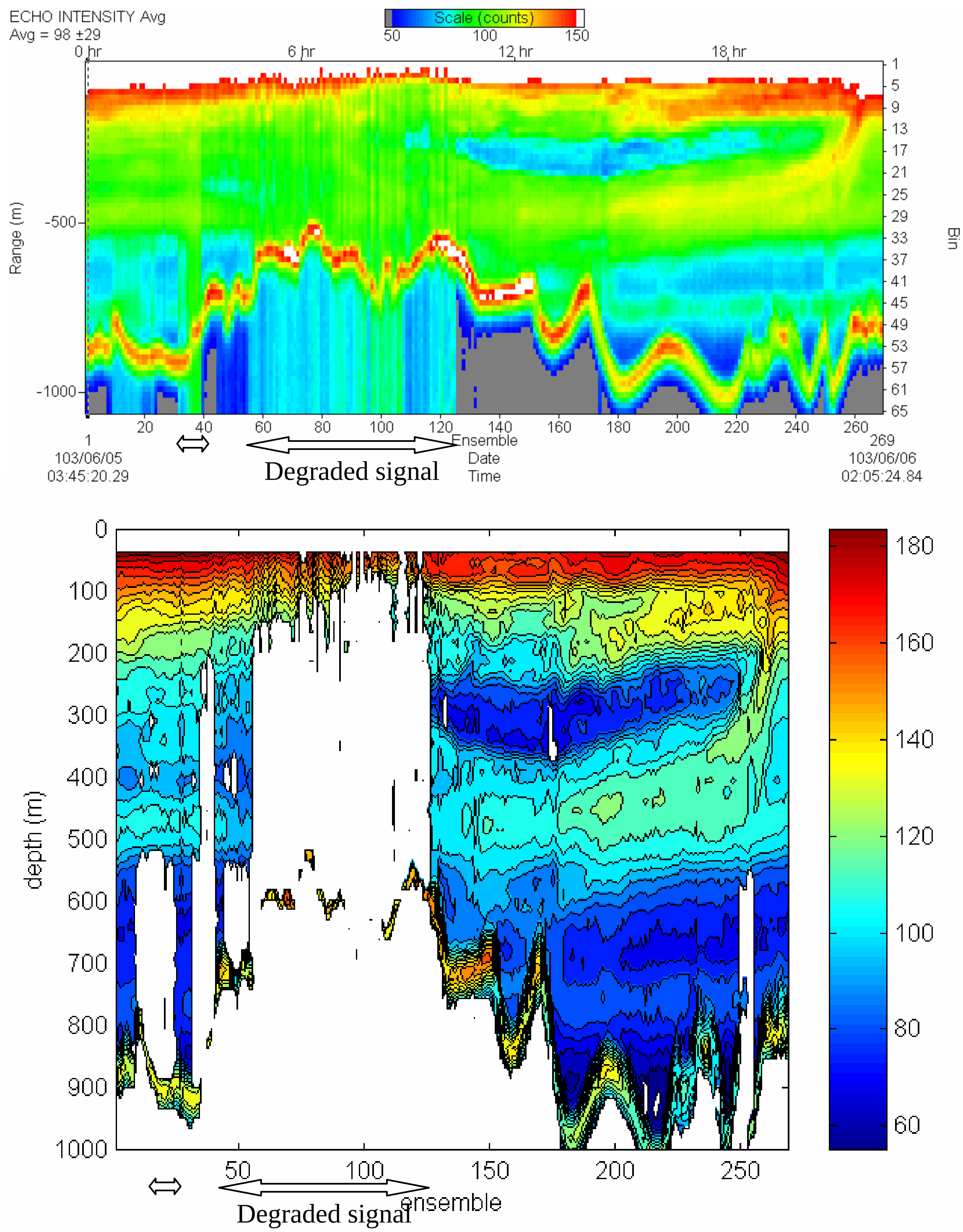


Figure 6. 38-kHz ADCP RABI color contour plots from WinADCP and MATLAB for June 5, 2003. Degraded data at ensembles 33-40 and 55-125 can be seen in the WINADCP plot (top). Poor quality data such as these from <80% beam agreement not included in the data set after processed using MATLAB and shown in white (bottom). High intensity return from the bottom can be seen in both plots between 500 to 1000 meters.

profiling range. The range for the 38-kHz ADCP is about 1000 meters, compared to only about 300 meters for the 153-kHz ADCP. However, a disadvantage of the 38-kHz ADCP is that the vertical bin resolution is averaged over 16 meters, which looses some of the detail that can be obtained with the 153-kHz ADCP 4 meters bins averages (Figure 7).

Discussion

Previous acoustic surveys with hull-mounted ADCPs have been conducted in the Gulf of Mexico with a 153-kHz ADCPs. At that frequency, the survey profiled the upper 300 meters and provided data on zooplankton variability based on various physical circulation features (Zimmerman, 1993; Ressler, 2001). Simultaneous net tows with these surveys found the scattering organisms to be mainly small crustaceans, siphonophores, pteropods, and small fish (Zimmerman and Biggs, 1999; Wormuth et al., 2000; Ressler, 2002). Another hull-mounted survey with a 300-kHz ADCP profiled plankton in the upper 100 meters (Sindlinger, 2003), and a moored 300-kHz ADCP showed temporal variability of plankton (Scott, 2001).

Since the sound attenuation coefficient and beam spreading factor for the phased-array 38-kHz has not been experimentally obtained, raw count signal intensity of the scattered sound received at the transducer was used for this study. Since the same instrument was used consistently in the same location on the same ship for multiple cruises, intensity profiles from different cruises can be compared to each other.

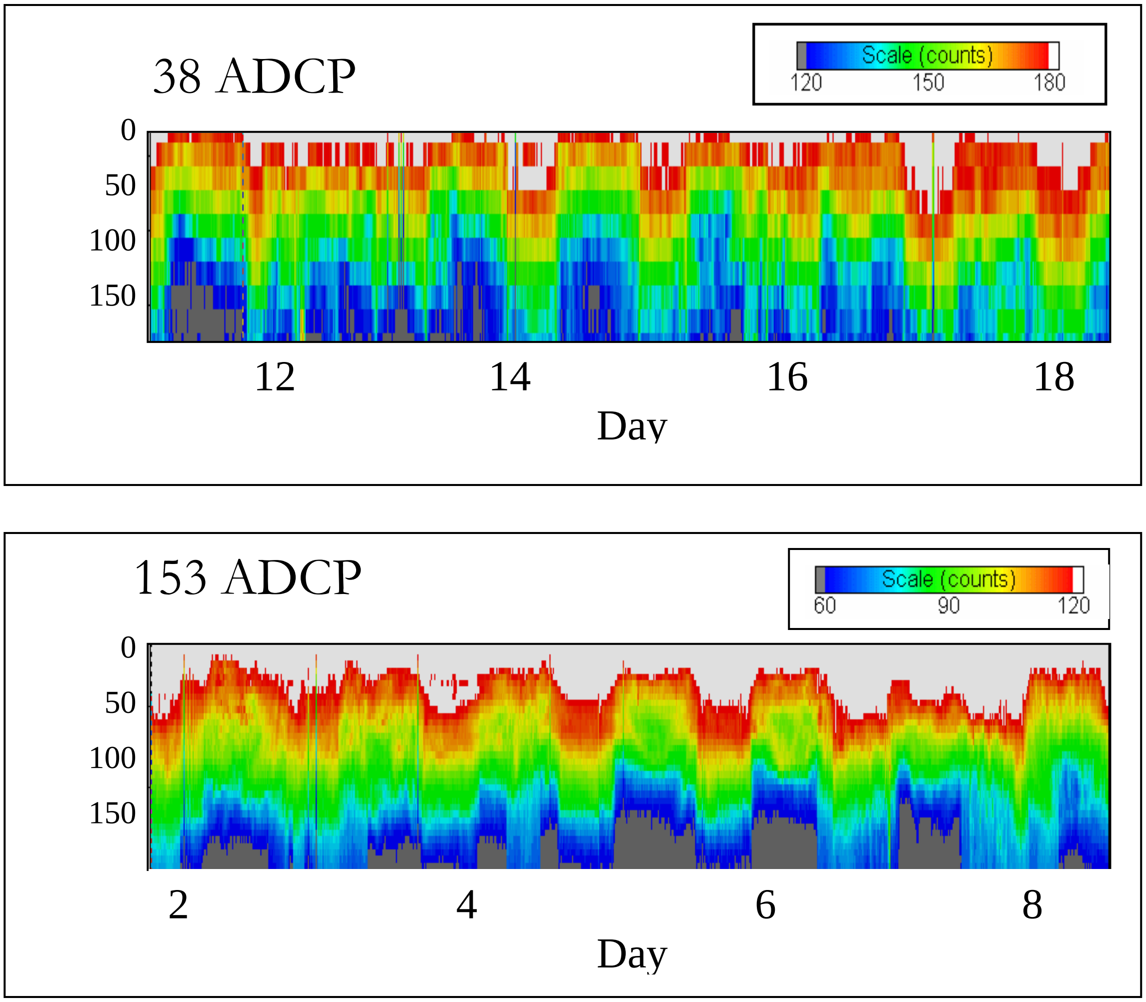


Figure 7. Comparison of resolution size between 38-kHz ADCP and 153-kHz ADCP records. WinADCP plots for both instruments are shown for the upper 200 meters. Vertical bin size is 16 meters for the 38-kHz ADCP, and 4 meters for the 153-kHz ADCP.

However, different vertical bins have been, and will continue to be discussed qualitatively rather than quantitatively in the proceeding chapters.

Traditionally, with the multi-piston transducer ADCPs, backscatter strength has been converted to an echo intensity value by the following equation:

$$EI = SL + SV + constant - 20\log(R) - 2\alpha R$$

where; EI is the echo intensity (dB), SL is the source transmitted power (dB), SV is the water-mass volume backscattering strength (dB), α is the absorption coefficient (dB/meter), and R is the distance (meters) from the transducer to the depth cell of interest (see R.D. Instruments, 1996). Although backscatter signal has generally been converted to echo intensity based on regression curves, large errors can occur in the conversion of acoustic energy to biomass if the energy/biomass relationship approximated from simple regression curve changes due to other factors (Stanton et al., 1994). For example, several other variables such as scattering animals shape, orientation, and density have been shown to all influence the energy of the backscatter return (Stanton et al., 1994; Benoit-Bird and Au, 2002). Specifically, dense-bodied animals usually scatter sound more strongly than gelatinous organisms, and fish and marine mammals with air-filled swim bladders or lungs are strong scatterers (McGehee et al., 1998).

Although ADCPs have proven to be useful in relative biomass estimates, resolution for individual targets is generally impractical because ADCP backscatter data are averaged over time and depth. Other instruments and techniques are being developed to obtain high resolution for imaging individual targets such as fisheries echosounders that use multiple frequencies. Goss et al., (2001) has developed a technique using a Simrod EK500 echosounder at 38 and 120-kHz to detect weak-target squid that are normally non-detectable by other methods. A downward looking high frequency (307-kHz) ADCP was able to track the migrations and movements of a herring school (Zedel et al., 2003). Although the ADCP could not measure the speed of an individual fish, when the whole school was analyzed, horizontal swimming speeds were recorded that approached 50 cm s^{-1}. Another acoustic survey with a towed DT4000 Digital Scientific Echosounder with a simultaneous video survey of foraging marine mammals, showed a strong correlation between the prey school and the predator abundance (Thorne and Thomas, 2003). These different varieties of acoustic tools are increasing the horizontal and vertical range of oceanographic biological surveys being conducted. The instrument and technique used for acoustic surveys depend on the characteristics of the targets, and the purpose and intended results for the study.

The ADCP is an oceanographic tool that can simultaneously measure both current velocity and backscatter intensity. Another benefit that the ADCP has over echosounders is that the ADCP averages backscatter return from four acoustic beams. This variability among the beams allowed a parameter for data quality control used in this study. Low signal to noise due to high ship speeds was identified by agreement among the four beams, and any data with less than 80% beam-agreement were not used.

CHAPTER III

DIEL VERTICAL MIGRATIONS AND THE DEEP SCATTERING LAYER OBSERVED FROM THE 38-KHZ ADCP

Introduction

Diel vertical migration (DVM) is a phenomenon observed in many planktonic organisms, both marine and freshwater. The general pattern is for these animals to ascend from depths beneath the photic zone near dusk, feed in the prey abundant surface waters at night, and then descend again to dark waters near dawn. It is hypothesized that the vertical migrations lead to a reduced rate of predation of the migrating animals, because in the dark the animals are not as visible to most predators (Han and Straskraba, 2001). However, other benefits to DVM may exist including a reduced metabolic rate at lower ambient temperatures encountered at greater depths.

DVM is more common in larger and more highly pigmented species, most susceptible to visual detection by predators, and is also more common when planktivorous fish are abundantly present than times when they are not (Hays, 1995). One of the costs of DVM to the animal is that they generally are fasting during the daytime hours when at depth and so, have a reduced feeding rate than when feeding during the night in the surface where food is abundant. In addition, there are more obvious costs associated with locomotion. Not all individuals of a species always vertically migrate. Individual variability in daily migration is influenced by their physical condition, with animals with larger lipid stores migrating to the surface less often than those individuals that can not afford a lower feeding rate (Hays et al., 2001). So the question whether or not to make the migration to the surface to feed may be an individuals assessment of the combined risks of predation and costs of locomotion compared with its hunger-driven feeding and metabolic depression while at depth.

Traditionally, studies of the diel migrations of micronekton were generally done by collecting samples from net trawls. Opening and closing nets targeted at specific times in specific depth bins will give a profile for a species abundance at each depth trawled. Pearcy et al., (1977) used an opening and closing Isaacs-Kidd midwater trawl from 0 to 1000 meters in the eastern Pacific near Oregon to describe diel vertical migrations common for several species of fish and shrimp. Most species occupied depths of 0 to 50 meters at night and descended to 300 to 500 meters during the daytime, although migratory species were found down to 1000 meters. Hopkins and Baird, (1985) also reported vertical migrations of pelagic organisms by similar sampling techniques in the eastern Gulf of Mexico.

Although net trawling will provide specimens that will allow taxonomic categorizations, there are however, many problems with using net trawls to make species abundance estimates. These include biases associated with individuals' net avoidance behaviors, as well as choosing the optimal mesh size and towing speed to include the size range for the targeted animals. It is difficult to obtain confidence that the net sample is an unbiased representation for the population, so net samples are oftentimes considered an underestimate of the population.

An alternative method for studying vertical migrations is a non-invasive acoustic approach. Francescini et al., (1970) used acoustic reverberation measurements at 12 kHz to reveal the existence of 4 to 5 deep scattering layers (DSL) in the Gulf of Mexico. Such DSLs are seen when a number of animals occupy the same depth, or light level. These layers will scatter sound and appear in an acoustic record as a band spanning a specific depth range. Subsequent acoustic surveys of zooplankton with 153-kHz (Heywood et al., 1991; Zimmerman and Biggs, 1999; Ressler, 2001; Wade and Heywood, 2001) and 300-kHz ADCPs (Sindlinger, 2003) also documented diel patterns of zooplankton abundance. Because of their relatively high frequency of operation, these ADCP surveys were limited to the upper 300 and 100 meters respectively, and did not resolve the daytime depths for most species. These near-surface ADCP plankton surveys were matched with net-collected biomass, as well as, with hydrographic surveys which allowed regional variability to be correlated with circulation eddy features.

Sound travels on average at 1500 m s^{-1} in seawater, so the wavelength for the 38-kHz frequency instrument can be calculated by the following equation:

$$c = f\,\lambda \qquad \qquad [150000\ cm/s = 38000\ /s * \lambda]$$

where c is the speed of sound in seawater, f is the operating frequency, and λ is the wavelength (RD Instruments, 1996). Since the wavelength of the 38-kHz sound is about 4cm, the theoretical minimum size of scatterers which can be resolved is approximately one half to one quarter of the wavelength, or 1 to 2cm. In the study area, animals in the size range of centimeters include decapods, euphausiids, small fish, and squid.

In this chapter, the results of the ADCP backscatter survey (both 38 and 153-kHz broadband) are largely a descriptive analysis of the main deep scattering layer and DVM. Vertical migrations are described according to migration rates, timing of the migrations, and the influence of common circulation and hydrographic features.

Methods

RABI data were analyzed for vertical migration rates for each day of three cruises; SWSS03 habitat May 31 - June 21, 2003, DGoMB4A June 1-14, 2002, and DGoMB4B August 2-13 2002 (see Table 1 in Chapter I). Scattering layers were scored as one if there was a visibly distinct separation in the color contour plots of relative backscatter for the four acoustic beams. Vertical migration rates of the migrating animals were calculated by the vertical change of depth versus time of the scattering layer (Figure 8). In all the records, once the organisms near the targeted depth, or targeted light level, the migrations slowed resulting in a curved slope in the backscatter. However, vertical rates were calculated by change of vertical distance traveled over the change in time where the migration appears as a straight line.

Regional variability in relative backscatter signal was compared with sea surface height (SSH) altimetry data from the TOPEX/POSEIDON and ERS satellites to identify local regions of cyclonic and anticyclonic mesoscale eddy activity. Sea surface salinity data, collected during the SWSS cruises using the ships onboard flow-through system, was used to identify the area of freshwater input from the Mississippi River, and its potential impact on the daytime depth of the main DSL.

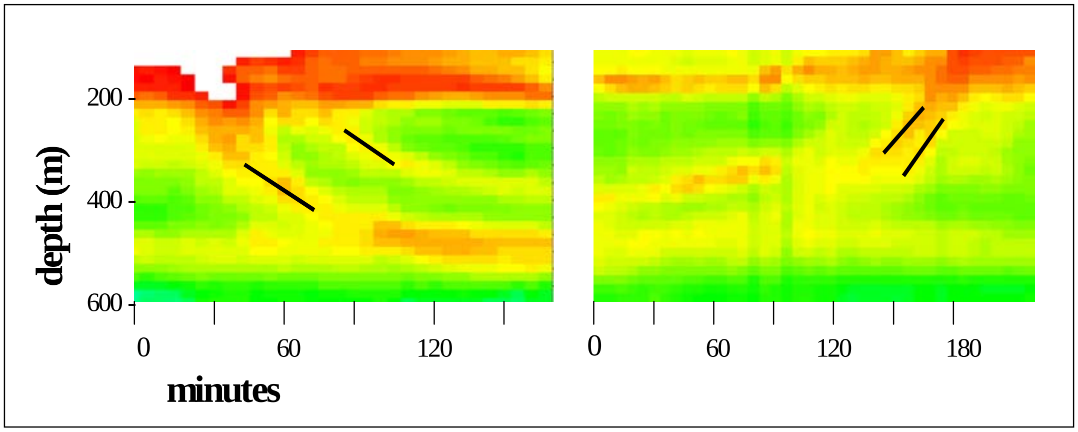


Figure 8. Vertical migration rates were calculated from the change in depth with time at mid-migration. Typical patterns for the diel migrations obtained from the 38-kHz ADCP RABI data were non-linear. This indicates that the animals tend to slow down or speed up their descent as they approach or move away from the depth of their preferred level of light. However, rates were calculated over a linear section of the migration (shown by the overplotted lines.)

Results

Rates of diel vertical migrations

For each diel migration, there were between 1 to 4 individual migrating scattering layers detected visually using both the ADCP manufacturer software, WINADCP, and vertical profiles constructed using the computer program MATLAB (Figure 9). Although the layers usually overlapped to some degree, especially near the surface, they were distinguishable either because they began migrating earlier or later in the day in relation to each other, they migrate at a different rate and the layers become separated, or they stop their migrations at different depths and form separate DSLs.

The average rate of vertical migrating rates of the scattering layers was 6.1 cm/sec for the descending migration and 6.6 cm/sec for the ascending migration. The rates ranged from 1.6 cm/sec to 12.4 cm/sec (Table 3). If vertically migrating animals greater than 1 cm can be resolved, it suggests that this ADCP may have directly tracked vertically migrating organisms moving on the order of one to several body lengths per second.

The range of sizes and calculated vertical migrating rates includes several different scattering layers presumably containing different species. Because of the vertical overlap in the layers, especially in the surface at night, it was not possible to track the same group over more than a day of the record and one group could not be distinguished from another while they were aggregated at the surface at nighttime. Analysis for a particular DSL was, therefore, limited to within each day rather than

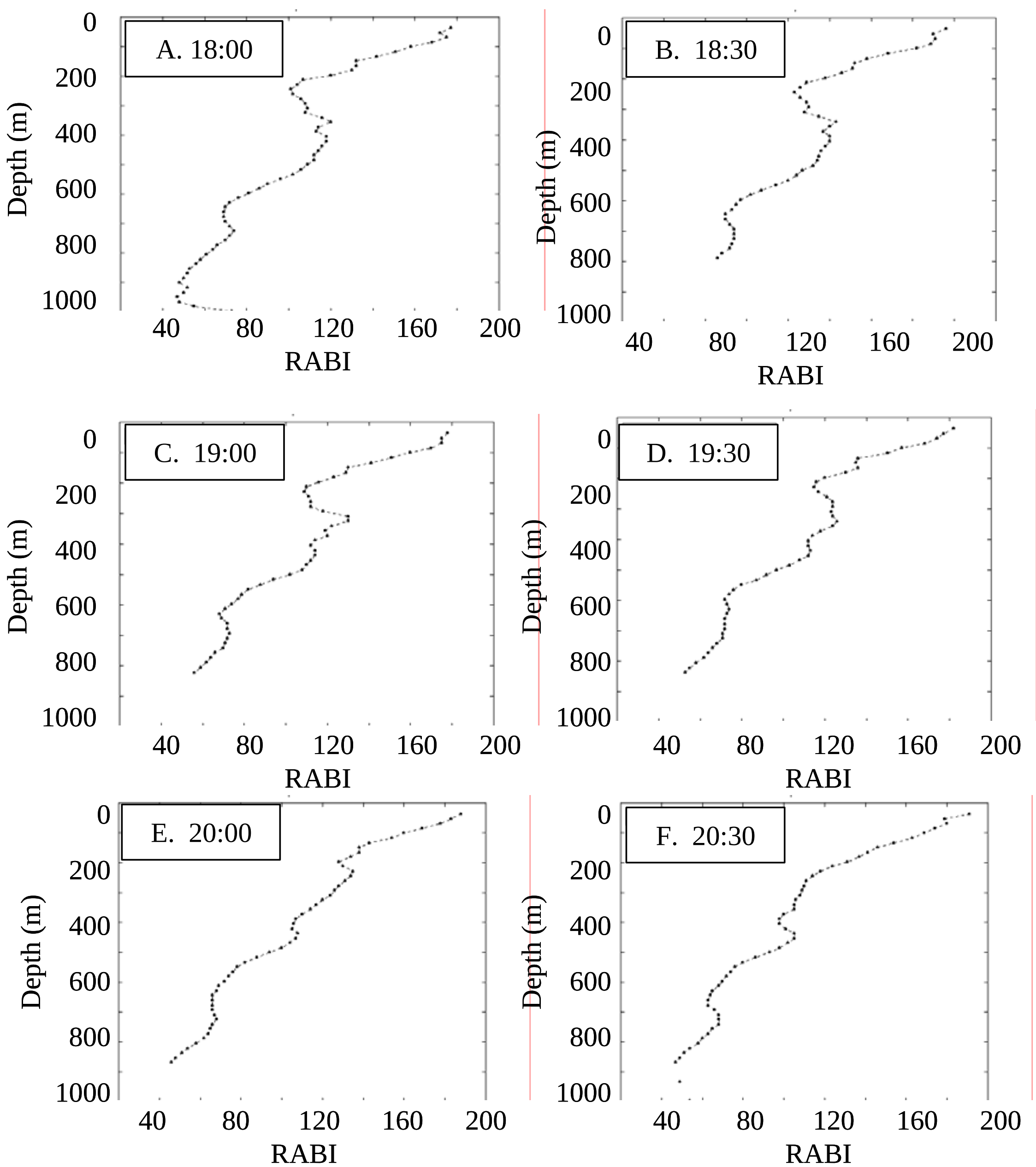


Figure 9. Vertical profiles of RABI from the *R/V Gyre* cruise 03G06, shown in 30-minute increments. As it gets later in the day, scattering layers can be seen ascending to surface depths. Mean June sunset time was 19:53 CST, which occurs between panels D and E.

Table 3
Average and range of vertical migration rates calculated for diel vertical migrating organisms

	Descending	Ascending
Average Rate (cm/sec)	6.1	6.6
Minimum Rate (cm/sec)	1.6	3.2
Maximum Rate (cm/sec)	12.4	10.7

comparing one day to another. No significant variation for vertical migration rates were observed between hydrographic regions, and areas of strong upwelling and downwelling did not appear to influence on the vertical migrating rates for these species since vertical currents are usually small compared to the migration rates of the animals.

Vertical migrations follow a very consistent day/night cycle. For DVMs during the SWSS03 LEG1 cruise, scattering layers began the descending migration out of the surface waters between 04:00 and 05:15 local CDT (Central Daylight Time). This is nearly one hour ahead of the mean June sunrise time 06:17 CDT, obtained from the U.S. Naval Observatory online database (available at http://aa.usno.navy.mil/data), which means that migration is likely triggered by twilight well before actual sunrise. The scattering layers then returned to the surface just after sunset between 20:30 and 21:00 local CDT, when the sunset time was 20:04. An appropriate shift in migration timing was observed during an August DGoMB cruise. In August, the mean sunrise time was at 06:40, half an hour later than the cruise in June. Descending migrations out of the surface left between 04:40 and 05:40, and migrations returned back to the surface between 20:15 and 20:30 when the mean sunset time was 19:50.

Comparison of 38-kHz ADCP backscatter with simultaneous 153-kHz data

During the DGoMB cruises, a broadband 153-kHz ADCP was running simultaneously with the 38-kHz ADCP used in this study. The distinct diel signal is apparent in the RABI color contour plots (Figure 10). The bottom panel shows a one and a half day RABI record for the 153-kHz ADCP, and the top panel shows a one and a half day RABI record for the 38-kHz ADCP over the same vertical range. Migrating organisms descend out of the vertical scale of figures during daytime hours and return again during the nighttime hours.

Although the 153 and 38 kHz instrument receives backscatter return from different sized targets (theoretical minimum size for direct detection is 0.25cm and 1cm, respectively), the DVM is a common pattern in both size groups. The diel changes are similar to previous surveys in the Gulf of Mexico with a 153-kHz narrowband ADCP in which relative backscatter was converted to absolute values of acoustic volume backscattering strength, in units of decibels (Sv) (Ressler, 2001). These converted data track the scattering layer as it leaves the upper 200m and descends to the main deep scattering layer (at about 450 to 500 meters). Because the depth range of the 153-kHz ADCP does not include the daytime DSL for most animals, the complete vertical range of migrations are usually not visible. However, the 153-kHz ADCP gives finer spatial resolution than the 38-kHz, and more details in the surface are exposed. For example, in the lower panel of Figure 10, a DVM layer can be seen beginning the daytime descent later (becomes visible at 08:00 CDT) than most other migrating animals and forms a scattering layer at about 80 meters. The timing of the vertical migrations was the same as the timing observed with the 38-kHz ADCP, although the onset of vertical migration within the shallow, 80 meters scattering layer was generally not detectable with the 38-kHz ADCP.

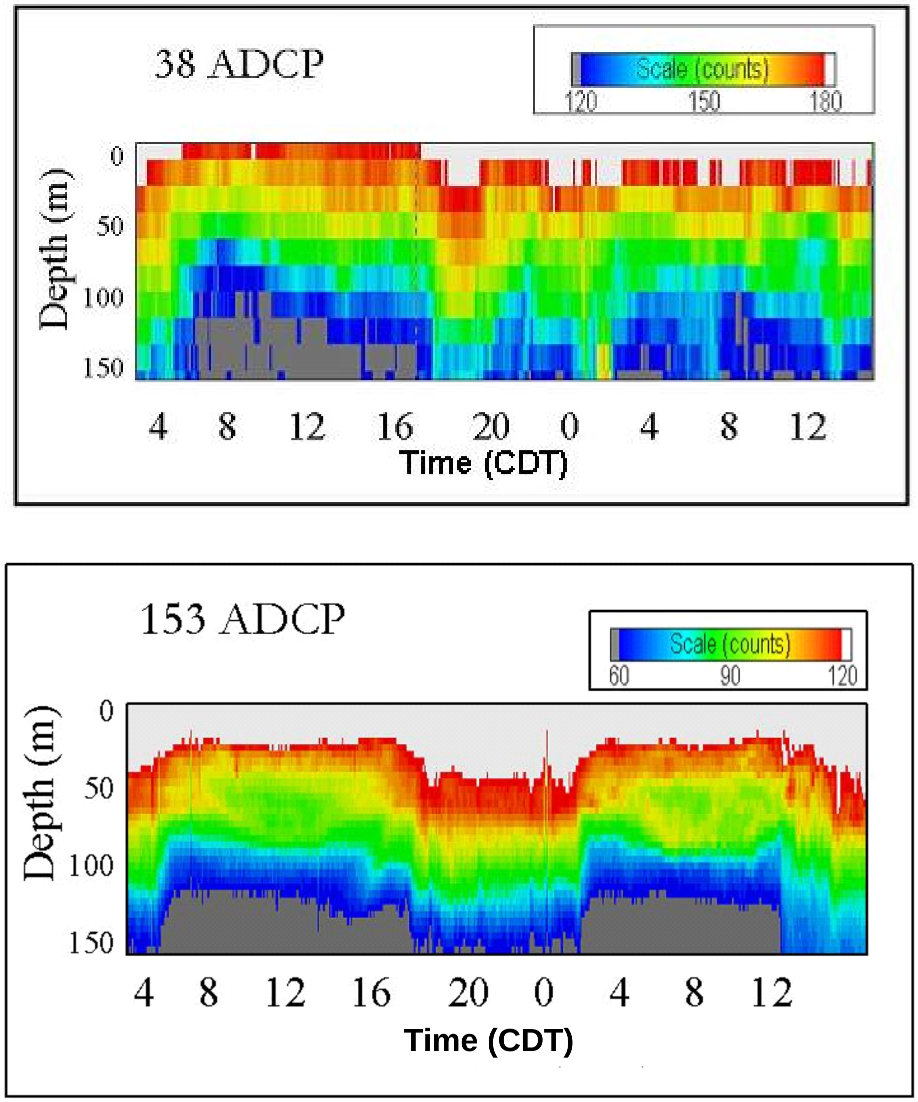


Figure 10. Comparison of 153 and 38-kHz ADCP RABI over 36 hours. 38-kHz ADCP example was taken from SWSS03 Habitat cruise, 153-kHz ADCP example was from DGoMB August, 02 cruise. ADCP comparison showed same phase for timing of migrations. Vertical bin size is 16 meters for the 38-kHz ADCP and 4 meters for the 153-kHz ADCP.

Regional hydrographic variability

To compare acoustic backscatter in different hydrographic features, I present two case studies from the summer of 2002 and 2003 when the ship transited across cyclonic and anticyclonic circulation features. Between August 8 and 10, 2002 during the DGoMB cruise, the ship traveled from a deepwater cold-core mesoscale cyclonic eddy into the Loop Current (Figure 11). Cold-core cyclonic features, generally associated with upwelling of nutrients, are presumed to have higher primary productivity, which in turn should result in higher standing stocks of epipelagic zooplankton and their predators. When the 38-kHz ADCP RABI data were compared between these two areas, the cyclone showed slightly higher relative backscatter in the daytime main deep scattering layer than did the anticyclonic Loop Current (average counts of 130 and 110 respectively.) There were, however, no noticeable differences in the depth of the main DSL or the maximum depth at which scatterers was detected (about 800 meters.)

A similar comparison was made between cyclonic and anticyclonic features along the continental margin during the SWSS cruise in June, 2003. The ship transited the northern periphery of a large Loop Current eddy on June 8, and then traveled into the cooler water cyclone on June 15 (Figure 12). There was higher relative backscatter in the daytime DSL on June 15 than June 8 (averages of counts of 130 with patches up to 145, compared to average of 120 respectively.) However, the higher backscatter in the cyclone may be a result of proximity to enriched coastal waters as well as to local divergence and nutrient upwelling.

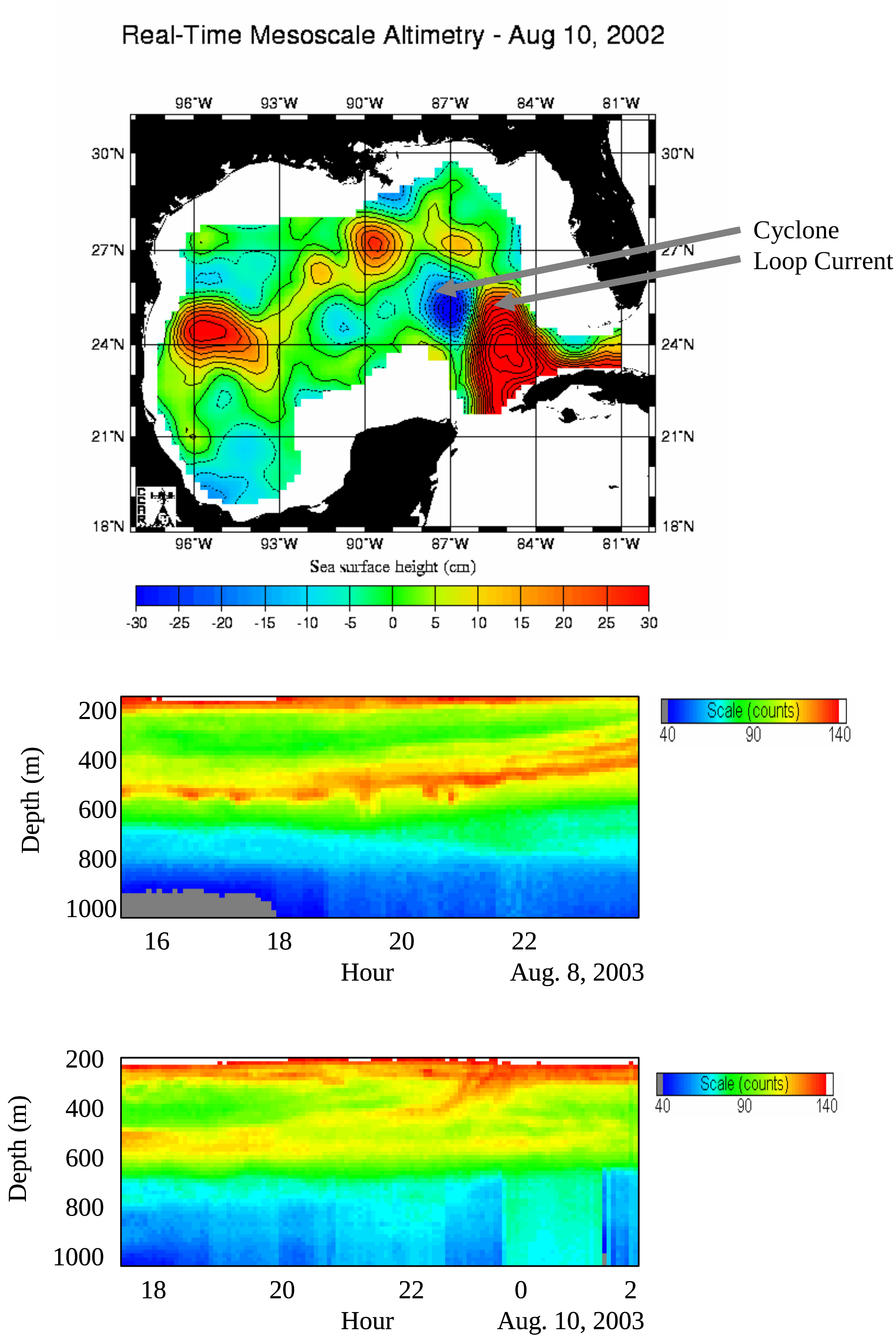


Figure 11. Comparison of 38-kHz ADCP RABI from cyclone (middle) and Loop Current (bottom) during the DGoMB4B cruise.

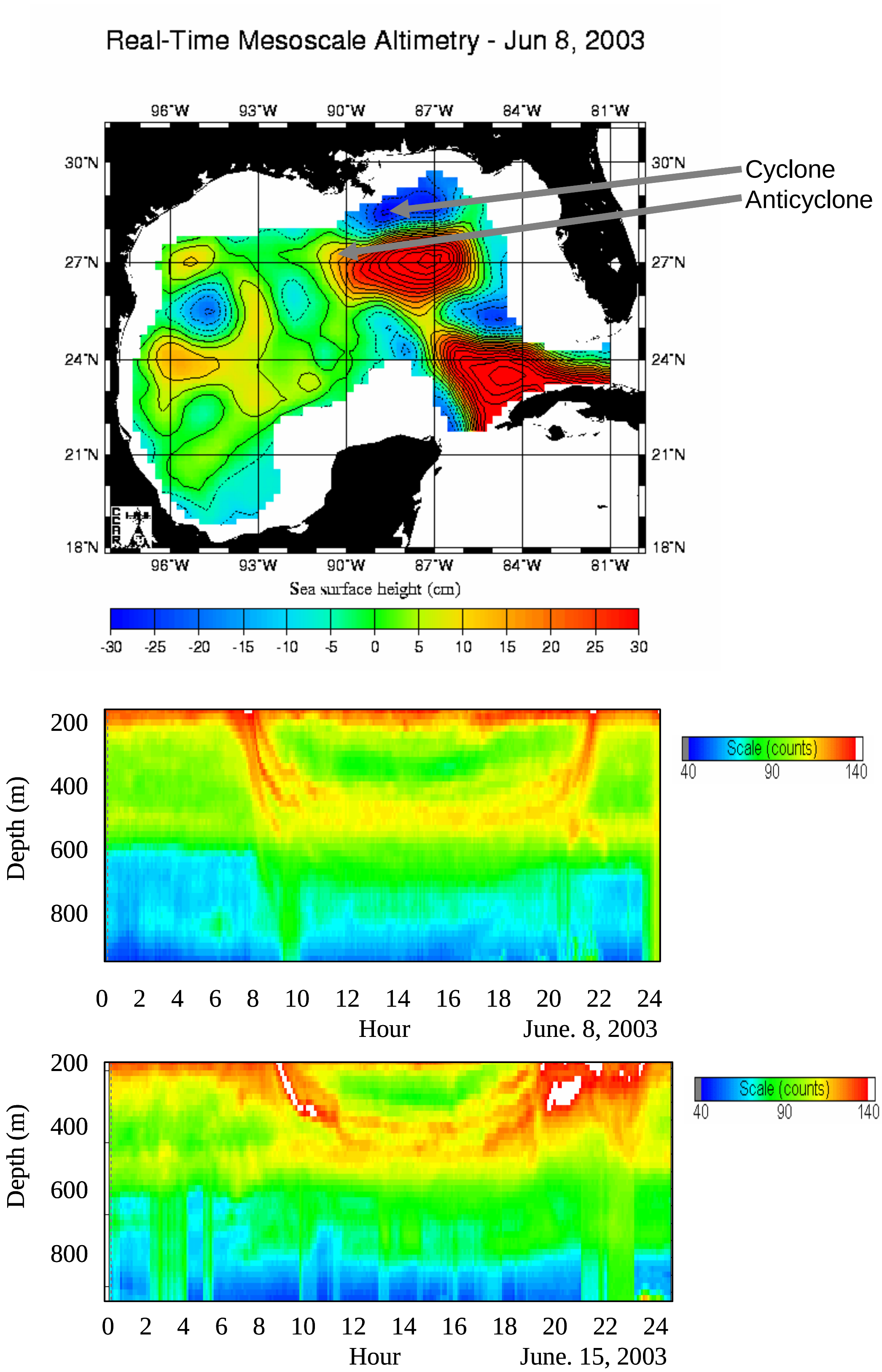


Figure 12. Comparison of 38-kHz ADCP RABI from an anticyclonic region (middle), and cyclonic region (bottom) during the SWSS03 Leg 1 cruise.

In a 20 day time series plot of the RABI record over the entire cruise (Figure 13), the daily signal peaks due to the vertical displacements of the DVMs are quite prominent. For most daily signals, the high intensity peaks at 100 meters coincide with the daily low peaks at 500 meters. The 500 meter signal does not show as clear of a pattern because some migratory animals descend to scattering layers deeper than 500 meters and so they add a bimodal signal to shallower bins. There was generally more variability in RABI amplitude in the surface bins than in deep bins, which is probably due to a stronger impact of regional hydrographic variability near surface than in deeper waters. Backscatter signal at 100 meters had a higher nighttime average in the eastern region when circulation was generally cyclonic (cruise day 9-20) than in the western region where circulation was weak (cruise days 1-8). Daytime backscatter, represented as the lowest daily signal when migratory animals are in the DSL, was greatest on cruise days 8-10.

Mississippi River influence

The combined outflow from the Mississippi River and Atchafalaya Rivers has a strong influence on many biogeochemical processes of the northern Gulf of Mexico. They introduce large amounts of nutrients, both natural dissolved and particulate organic matter and anthropogenic sources from urbanization and agricultural fertilization. The large drainage area covers 41% of the contiguous United States. Increased nitrogen and phosphate concentrations lead to localized phytoplankton blooms, higher productivity, and hypoxia in some areas (Rabalais et al., 2002).

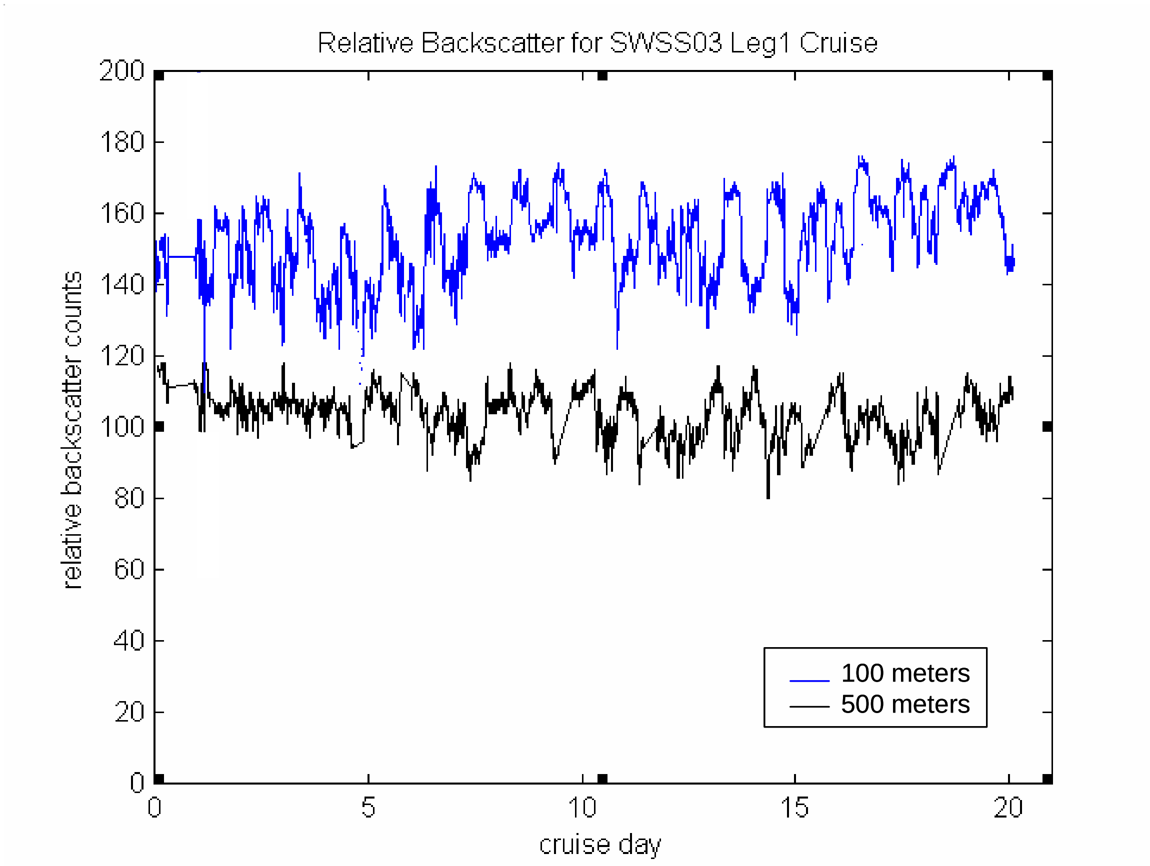


Figure 13. 38-kHz ADCP at RABI 100 and 500 meters for the SWSS03 Leg1 cruise. At 100 meters, there was generally one peak per day, whereas deeper bins had two peaks per day. Greater daytime backscatter near surface (between days 7 to 12) occurred in a region where slope eddies were in close proximity to the cruise track.

Shoaling of the DSL when the ship was in the Mississippi River outflow was observed in the 38-kHz ADCP backscatter data. Analysis of CTD data have shown that as freshwater enters the Gulf of Mexico at Southwest Pass, LA, it generally stays as a buoyant plume at the surface and covers a narrow outflow width (Fletcher, 2004). During the SWSS03 Leg1 cruise, SSH data shows that the Loop Current extended far north onto the continental margin, and was in close proximity with a counter rotating cyclone located to the east. These conditions caused the narrow band of fresh Mississippi River water to become entrapped between the two eddies, creating a strong, distinct frontal boundary between the two, with subsequent entrapment off-margin into deeper water.

On June 12, 2003, as the ship crossed this front, the sea surface salinity went from 26 to less than 20 over a very short distance. This abrupt change in salinity coincided with strong shoaling of the main DSL (Figure 14). River water transports suspended particles and dissolved nutrients that enhance phytoplankton growth, both of which decrease light penetration. When the *R/V Gyre* transited the river outflow, the daytime DSL shoaled to about 200 meters from the surface, or less than half the daytime depth found in the adjacent blue water. This shoaling presumably indicates a decreased light penetration to deeper waters due to increased phytoplankton and sediment load in the surface. There were also relatively higher RABI signal in the DSL (>150) in this area, indicating there is higher biomass of the migrating species. Therefore, there can be significantly large variations in the abundance of DVM organisms over a small spatial

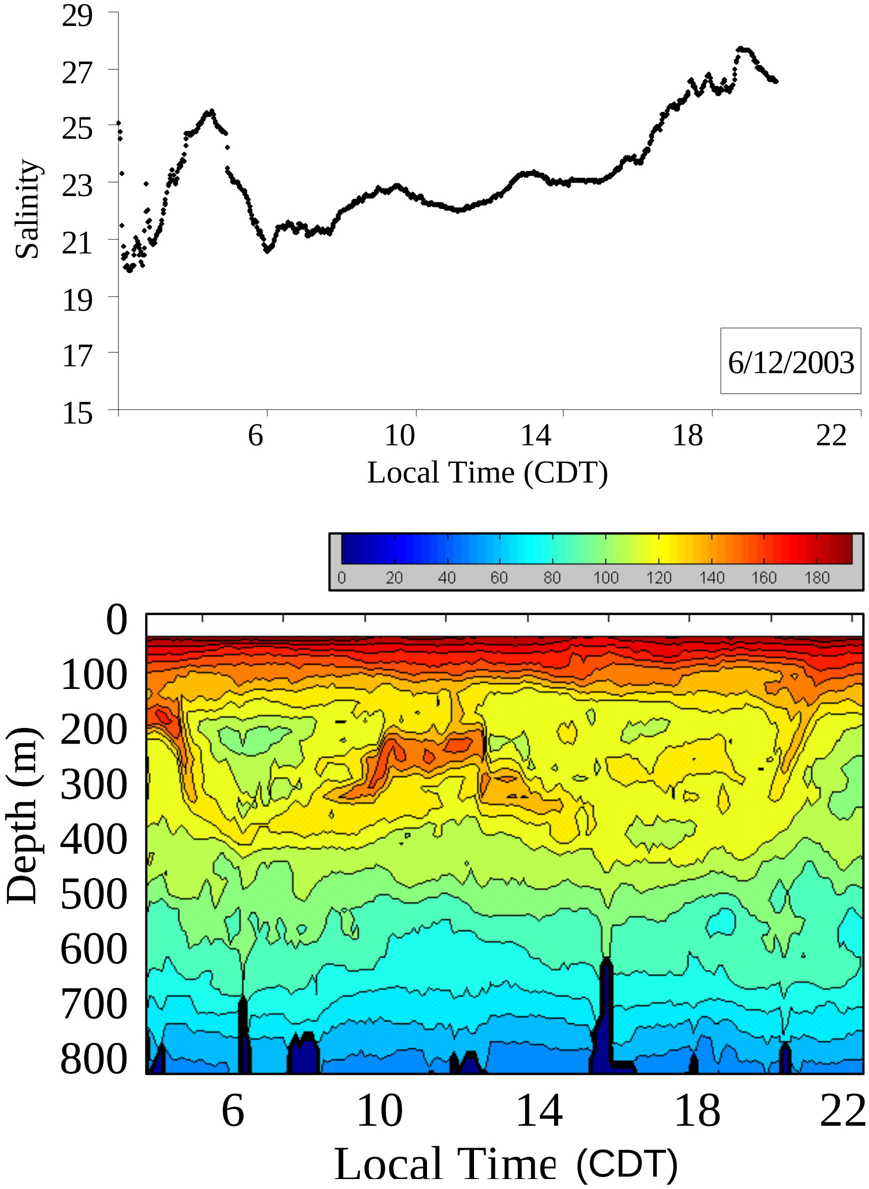


Figure 14. Sea surface salinity and RABI profile as the *R/V Gyre* transited the Mississippi River outflow plume on 6/12/2003. When the surface salinity decreased due to fresh river water input, the daytime depth of the main DSL shoaled to 200 to 350 meters below the surface, or 200 to 250 meters more shallow than the DSL observed in the adjacent blue water.

scale, and may also suggest that there is relatively little horizontal movement of these scattering organisms over this time scale since there was such a strong horizontal change.

Discussion

This descriptive study of the DSL and rates of vertical migrations was motivated by the first backscatter survey in the Gulf of Mexico with a 38-kHz ADCP. This frequency of ADCP penetrates deeper than the 153 and 300-kHz ADCPs, with backscatter signal received from as deep as 800 to 900 meters at times. The depth range of the 38-kHz ADCP was usually able to resolve the daytime depths of the main DSL. This allows a better view of DVM since different scattering layers, presumably corresponding to different migrating groups, can be distinguished. Timing of migrations and vertical migration rates were calculated and also helped to distinguish separate scattering layers.

Although previous studies have used higher frequencies of ADCPs when studying DVM, the diel pattern remains the dominant feature in this and higher frequency studies. Sindlinger's (2003) spectral analysis of energy and time showed a peak at one cycle per day in all depth bins of a 300-kHz ADCP, reflecting vertical migrations into and out of the surface scattering layer. Since the vertical depth range for the higher frequency instruments only includes the upper half of the migration, there is one cycle per day. A peak centered around one cycle per day was also observed by Sindlinger in a moored deepwater ADCP at 880 meters, suggesting that some DVM may either descend to as deep as 880 meters in the western Gulf of Mexico, or that some benthic species may move into and out of the sediments. With a similar spectral analysis of the 38-kHz ADCP backscatter, we might expect to see a one cycle per day signal in the surface bins and also in the bins of the main scattering layer at 500 meters, but we should expect to see a peak at two cycles per day for bins between the surface and scattering layer. The two cycles per day would correspond to the times migrating animals are either ascending through the middle bins to the surface or descending again to the DSL.

A diel pattern was also observed with the 153-kHz backscatter data that was collected simultaneously with the 38-kHz ADCP backscatter data. This allowed the signal of the DVM from the two instruments to be compared to each other. The similarity of the timing and rates of the vertical migrations between the two instruments suggests that there is some overlap in the target size range and the instruments may be observing the same migrations near the surface. This could be due to the high density of organisms, especially near surface. As small targets aggregate together, they may become strong enough targets to be detectable even if they are individually smaller in size than the normal minimum size detection for the instrument (i.e. Rayleigh scattering). The diel pattern observed in this study with this 153-kHz ADCP is very similar to the volume backscatter (converted to Sv) by Wade and Haywood (2001), in their study of the influence of oceanic fronts on the mean volume backscattering strength.

The most noticeable variation in the pattern of backscatter from the 38-kHz occurred in the main DSL in the region of the Mississippi River plume. The daytime depth of the main DSL shoaled several hundred meters closer to the surface, presumably because migrating organisms try to stay at their normal light level when increased concentrations of surface particles block light penetration. Similar responses of vertical migrating organisms to alterations to the normal light level have been observed in freshwater lakes when DVM of *Daphnia* was significantly reduced in amplitude and magnitude by urban light pollution in a suburban lake (Moore et al., 2000). In the Gulf of Mexico, vertical migrations were found to be triggered in the middle of the day during a solar eclipse (Franceschini, 1970), indicating that DVM is predominately triggered by light levels rather than a biological circadian pattern.

Some regional variations in intensity were observed between days of the cruises in different locations that appeared to be due to passage in and out of mesoscale cyclonic and anticyclonic features. Although no quantitative analysis between bins was conducted due to the unknown absorption coefficient, the descriptive visual comparisons on the intensity of the scattering layers indicated that there was higher abundance of scatters in cyclonic than anticyclonic features. Wormuth et al., (2000) who sampled zooplankton and micronekton in cyclone and anticyclone eddies both directly with MOCNESS and IKMT trawls and indirectly with 153-kHz ADCP, found higher biomass in cyclones as well as a seasonal variation. Variations in backscatter intensity due to the passage in and out of hydrographic features tended to be more apparent in the upper 50 meters than deeper in the water column in previous studies (Zimmerman and Biggs, 1999; Sindlinger, 2003). Data from the 38-kHz ADCP also showed that there was more variability near surface than at depth.

Diel horizontal migrations have been observed in oceanic habitats in close off-shore waters surrounding islands (Benoit-Bird et al., 2001). Because the DSL could be observed quite close to shore, its horizontal as well as vertical movements were imaged. As the DVM layer ascended to the surface at dusk, its surface expression also expanded horizontally. At dawn, the DSL began to descend but in the shallow water was forced to move horizontally back out to deep water. Since there are few shallow water shoals at the shelf-slope break in the Gulf of Mexico, the extent of horizontal movement associated with the vertical migrations for the deep ocean could not be measured in a similar way. It would be interesting for a future study to determine if, and to what extent, there might be a horizontal component of the diel migrations in the open ocean. There may be additional strategies in the behavior of individuals to use vertical migrations as a mechanism for regulating their horizontal position. For example, migration behavior has been described in estuarine habitats, as individual larvae used vertical movements over the tidal cycle to maintain their location in the estuary rather than being flushed out to deep water, despite the net flow outwards (Garrison, 1999).

In summary, DVM has long been of interest to researchers and has been extensively studied. It is now widely accepted that the descending diel migration in daytime is a response to visually orientated predators, and the ascending diel migrations is in response to the need for optimal feeding at the surface at night. Many factors have been studied that appear to play a role on the characteristics of the DVM including seasonality of phytoplankton blooms (Dagg et al., 1998), population size of the migrating species (Andersen & Sardou, 1994), UV radiation exposure at the surface during the daytime (Rhode et al., 2001), individual energy reserves (Hays et al., 2001), and predator abundance (Han and Straskraba, 2001). All of these factors seem to determine the timing and depth of the DVM for different groups and for individual vertical migrating animals. The 38-kHz ADCP backscatter has allowed an expanded look at the depths of the vertical migration and the sorting out of the migration to different depth levels.

CHAPTER IV

DEEP SCATTERING LAYERS OF POTENTIAL PREY SPECIES IN THE GULF OF MEXICO SPERM WHALE DIVING RANGE

Introduction

The Sperm Whale Seismic Study (SWSS) is an MMS funded project that was developed to better understand sperm whale habitat and their response to anthropogenic sound produced during offshore seismic surveys (Jochens and Biggs, 2003). Seismic surveying of the sea floor to look for pockets of oil and gas uses sound to image the subsurface sediments. These seismic surveys occur in offshore waters of the Gulf of Mexico, which is the preferred habitat of sperm whales. Because sperm whales utilize sound for vocalization within their groups and for sonar-like feeding by a series of clicks, there is concern that the noise of seismic exploration may interfere with normal sperm whale behavior.

One goal of SWSS is to conduct controlled exposure experiments that will measure the behavioral response of sperm whales to a typical airgun source used in these seismic surveys. Results from these experiments may have important implications that could be used to potentially evaluate what effects seismic surveys have on sperm whales, and what actions would mitigate adverse effects on the whales.

Another goal of SWSS is to characterize the oceanographic habitat that sperm whales live in, including the chemical environment, the physical dynamics of the Gulf of Mexico system, as well as the biological interactions and food web structure. This study will help us to better understand the ecology and behavior of sperm whales, which will be important when attempting to set future regulations that attempt to protect these animals. It is essential to first get an idea of what are their normal range habitats and behaviors before trying to regulate their habitats.

The SWSS habitat characterization study measured a variety of biological, physical, and chemical parameters in the deepwater Gulf of Mexico. The focus of this section of the thesis is on the habitat characterization. The objective is to demonstrate a method that can be used to image scattering layers of presumptive prey animals living in deep waters below the main DSL. Although several studies have investigated the relationship between sperm whale distribution and oceanographic features (Griffin, 1999; Biggs et al., 2000; Davis et al., 2002; Sindlinger, 2003) there is generally a time lag between seasonal peaks in primary production and the occurrence of sperm whales, masking any kind of direct correlation (Jaquet and Gendron, 2002). Therefore, it would be beneficial to be able to directly relate sperm whale distributions with their main prey.

An accurate and reliable non-invasive acoustic survey is possibly an ideal method of studying sperm whale prey because there are many problems associated with the traditional net sampling methods that have been used in the past (see Chapter III). From stomach content analysis, sperm whales are known to feed primarily on medium to large sized squid and occasionally some large fish (Santos, 1999; Santos et al., 2002). These animals are too quick to be representatively and consistently surveyed by trawl samples because of net avoidance, and net sampling is time consuming and expensive to operate. Ways to overcome these problems have been developed including bigger and faster towed nets and using strobe lights to surprise and temporarily shock squid preventing net avoidance (Wiebe et al., 2004). Still, trawl samples are often underestimates of the actual population. Therefore, it has previously been nearly impossible to relate sperm whale distribution directly to the distributions of their prey (Jaquet and Gendron, 2002).

Because of the 16 meter vertical extent as well as the 5-minute averaging of each of the component depth bins, it is unlikely that a 38-kHz ADCP will receive a strong signal directly from individual squid. However, this study will focus on the depth range below the main DSL, in the secondary scattering layers that are likely to be the source of prey for the deep living squid. Compared to previous Gulf of Mexico ADCP surveys, backscatter targets from the 38-kHz ADCP should be one to several trophic levels higher, and so, in theory they should be more closely correlated to the distribution and abundance of sperm whales.

A hull mounted phased-array 38-kHz ADCP was used during the SWSS and DGoMB cruises in 2002-2003 to obtain deep water current data as well as relative backscatter to as deep as 1000 meters. Scattering layers were seen in the ADCP backscatter data at the main daytime DSL at 450 to 500 meters as well as deeper secondary scattering layers down to 800 meters. Variations in the presence and location of deep scattering were observed and is believed to be associated with the dynamic physical circulation features of the Gulf of Mexico, including Loop Current eddies and freshwater inputs. Simultaneous acoustic surveys of sperm whale detections with towed hydrophone arrays on the SWSS cruises provided data on the presence and absence of whales. Nighttime trawling to depths below the main DSL provided samples of some of the likely prey organisms.

Methods

ADCP survey of deep scattering layers

Acoustic backscatter data used to analyze deep scattering layers (DSLs) in the feeding habitat of Gulf of Mexico sperm whales were obtained from a hull-mounted 38-kHz phased array during 2002 to 2003 SWSS and 2002 DGoMB cruises. SWSS program cruises were targeted along the 1000 meter isobath of the northern Gulf of Mexico basin where sperm whales have been encountered historically (Biggs et al., 2002). Data from the two DGoMB cruises were collected from the lower slope and from the deep basin area, generally not associated with frequent sperm whale sightings and used for comparison of the two geographic habitats.

Sperm whale diving profiles provided by SWSS colleagues from Woods Hole Oceanographic Institute (WHOI), were collected during SWSS tagging and controlled exposure experiments in which whales were tagged with a digital tag (DTAG) (Johnson and Tyack, 2003). DTAGs are temporary, non-invasive tags that use suction cups to attach the tag to a whale's back when at the surface. The DTAG records several hours of data including spatial orientation of the animal, ambient pressure and temperature, and audio recordings. Depth profiles obtained during two DTAG experiments were used for choosing the targeted depth bins of the ADCP backscatter record that corresponds to the depths to which the whales were diving and believed to be foraging. One profile obtained from tagging in 2002 shows a whale diving between 400 and 800 meters (Figure 15, top) and a profile from 2003 shows another whale diving consistently to 650 to 700 meters (Figure 15, bottom). Another sperm whale diving study which used a 3-D hydrophone array to record sperm whale clicks during diving also concluded sperm whales exploit prey in a large part of the water column below the main scattering layer (Wahlberg, 2002). The range of 600 to 700 meters was used as the targeted depth for the focus of the backscatter analysis, since this depth range is likely to contain the greatest number of the prey of the squid on which sperm whales prey.

38-kHz ADCP RABI and beam correlation were read using the ADCP manufacturer software WINADCP, and average backscatter was then imported into MATLAB. In addition to ADCP data, other sources used to characterize the habitat included sea surface height anomaly from TOPEX/ERS satellite altimetry, data from the *R/V Gyre's* onboard flow-through sea surface temperature and salinity sensors, 15°C depths from XBTs, and optical backscatter and fluorescence from CTD casts.

Two presence-absence evaluations were conducted on the number of days in which abundant scattering was detected at the targeted depth in the color contour plots. The first of these compared the slope region (800 to 1000 meters water depth) to the deep basin region (>1000 meters water depth), and the second to discern the influence of mesoscale circulation features (cyclone, anticyclone, confluence, no eddies). The slope versus deep basin comparison included 45 total daily records of good data. The eddy influence comparison included 34 total daily records. Eddy environments were characterized based on the ships location and the proximity to eddies as determined both

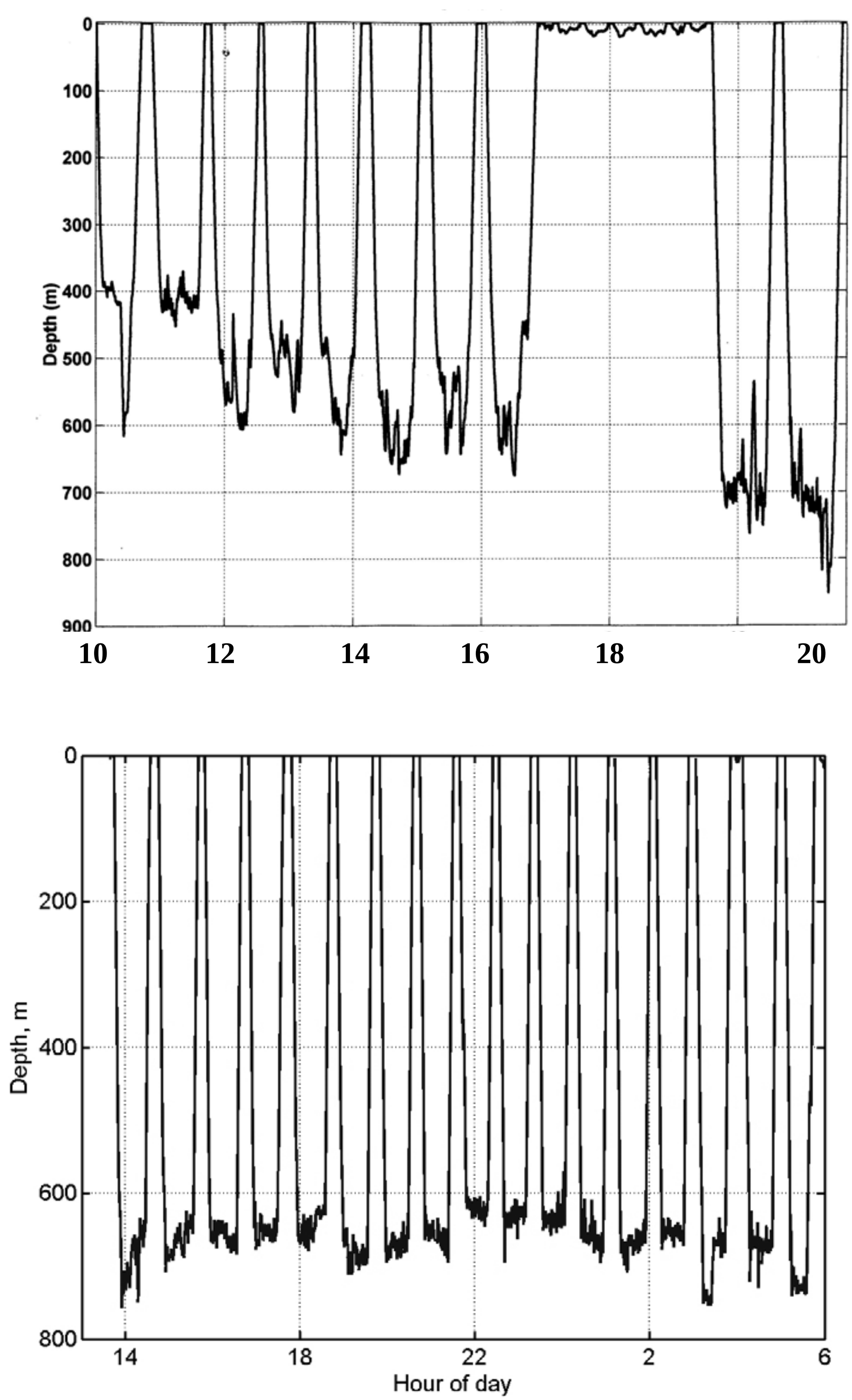


Figure 15. 2002 (top) and 2003 (bottom) sperm whale diving profiles obtained from short term digital acoustic tags (D-tag). Data and figure courtesy of Mark Johnson (WHOI).

from SSH images and 15°C depths (from XBT casts). To be positively counted for presence of scattering, the returns in the targeted depth must be greater than the expected background signal for the depth. Each daily record was viewed as a color contour plot which makes high intensity patches or layers visible. This method was used since the signal could not be converted to absolute values to allow for numerical comparisons between different depths, but it did allow for relative comparisons based on visual detection of high intensity scattering.

IKMT net trawling in deep scattering layers

A total of 25 net trawls were taken by Dr. John Wormuth (TAMU) during the SWSS03 habitat characterization cruise in June, 2003, with a 16 m^2 Isaacs Kid Midwater Trawl (IKMT). This trawl had mesh size tapering from 4mm to 0.33mm. Trawling was done at nighttime, with 2 trawls usually conducted per night, and depths were targeted to either 600 or 800 meters in addition to three shallow trawls made to 400 meters. The net was trawled at about 4 knots for between one and a half to three hours. An attached flowmeter and Seabird time, depth, and temperature sensor provided a depth profile of the trawl after the sample was collected. Wet displacement volumes of the samples were used to look for trawls that coincided with patterns in various hydrographic regions (cyclonic, anticyclonic, Loop Current) or high acoustic backscatter signal. Taxonomic sorting of the samples provided some examples of the DSL animals in the ADCP backscatter data.

Results

Slope versus deep basin comparison

RABI from the mid-slope of the northern Gulf of Mexico from SWSS were compared to RABI from the deep basin data from DGoMB. More frequent and more intense scattering layers in the targeted depth range below the main DSL (600 to 700 meters) were consistently observed in the slope region than in over the deep basin. Representative color contour plots from the deep basin and from the slope are shown in Figure 16. Vertical white areas are masked data where the between-beam correlation dropped below 80%. The targeted depth bin (600 to 700 meters), as well as the rest of the water column, show many more features above the background signal in the slope graph (top). Although there are relatively high backscatter counts in the DSL and vertical migrating layer, the deep basin graph (bottom) has very few other features beyond the background signal. Out of 34 possible days in the slope region, 21 days (about 2/3) had noticeable scattering in the targeted depth range below the main DSL (Table 4). In deeper waters (greater than 1000 meters) only 2 out of 11 days (less than 1/5) had scattering at the targeted depth.

When every ensemble over a whole cruise is averaged, peaks in the profile illustrate non-migrating scattering layers since the daytime and nighttime signals of migrations cancel. In Figure 17, the cruise average RABI profile from the SWSS03 and DGoMB 4B were compared. Overall, the two profiles are highly correlated (Spearman Rank correlation = 0.94). This reflects the fact that RABI generally decreased with increasing depth, and that a main DSL was observed between 400 and

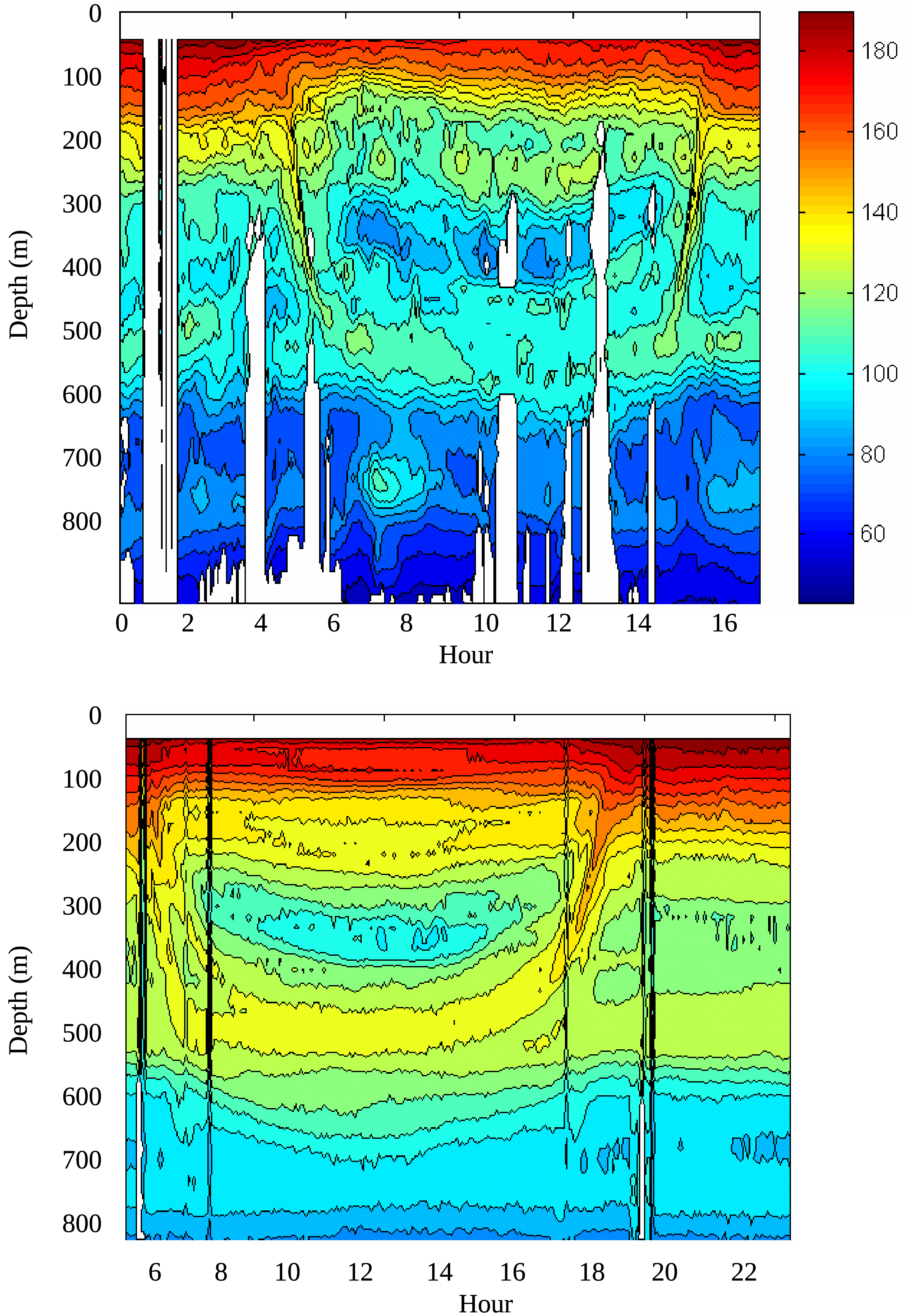


Figure 16. 38-kHz ADCP RABI running plots from the middle continental slope region (top) and the deep basin (bottom).

Table 4
A secondary DSL at the targeted depth range between 650 and 800 meters was present roughly 2/3 of the days in water depths less that 1000 meters, and 1/5 of the days spent in water depths greater than 1000 meters

Days in which there was a presence of a secondary DSL (>650m) out of the number of possible days in water less than or greater than 1000 meters.

Cruise	**< 1000 meters (800-1000)**	**> 1000 meters**
SWSS02 s-tag	5/9	0/1
DGoMB 4B	0/0	1/5
SWSS03 hab	9/15	1/2
SWSS03 s-tag	7/10	0/3
TOTAL	**21/34**	**2/11**

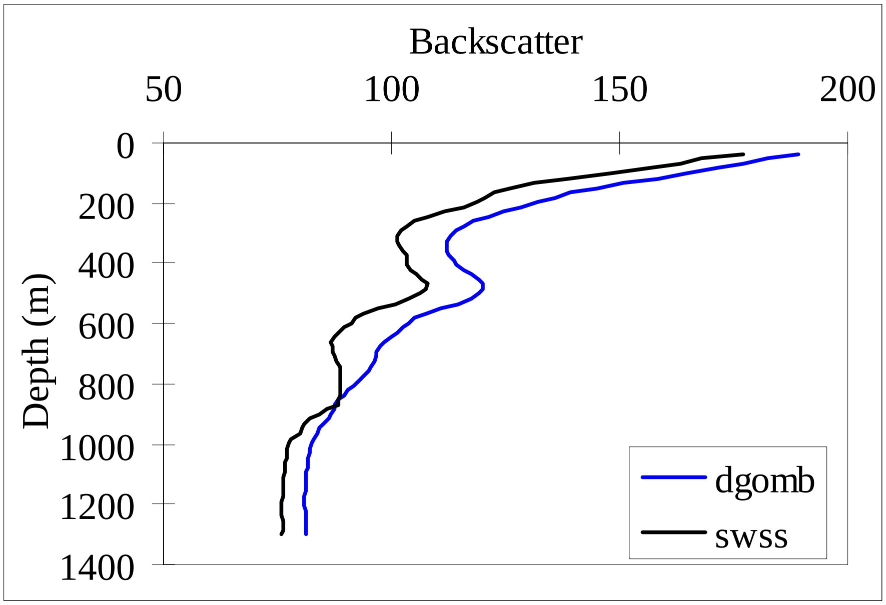


Figure 17. Cruise average 38-kHz ADCP RABI profiles for a SWSS and DGoMB cruise. Distinct scattering layers are observed at 400 to 600 meters for both cruises, but a secondary deep scattering layer at 700 to 900 meters was observed only during the SWSS cruise over the slope.

600 meters on both cruises. However a secondary, deeper DSL between 700 and 800 meters is observed only in the SWSS profile. A Spearman rank correlation for bins between 600 and 850 meters between the two cruises was 0.39, indicating dissimilar ranking order over those depth bins. This secondary peak likely represents a persistent, non-migrating, secondary DSL found over the slope region covered on the SWSS cruise that is not present during the DGoMB cruise that occurred over the deep water of the Gulf of Mexico basin.

Next, to show that the relatively high intensity DSL that occurred in the records was due to backscatter rather some kind of instrumentational artifact, optical backscatter (OBS) profiles from CTDs during DGoMB were analyzed. Although OBS is used for detecting particles many orders of magnitude smaller than the 38-kHz ADCP resolution, it is another resource that was available to compare possible scattering layers. Since the presence and concentration of particulate matter indicate the location and intensity of oceanic biogeochemical processes (Gardner et al., 1990), we might expect to see a larger OBS signal in areas or depths where organisms are aggregated. When the OBS profile was plotted, several peaks appeared at the similar depths as scattering layers of the 38-kHz ADCP (Figure 18). This profile, taken at 13:53 local time (CDT) on May 14, 2000, contains a very large peak at 150 meters.

The coinciding fluorescence peak indicates that this is the chlorophyll maximum at or around which vertical migrating scattering organisms may have concentrated (Figure 19). There is also a secondary maximum between 400 and 500 meters, corresponding to the daytime depth of the main scattering layers seen in the

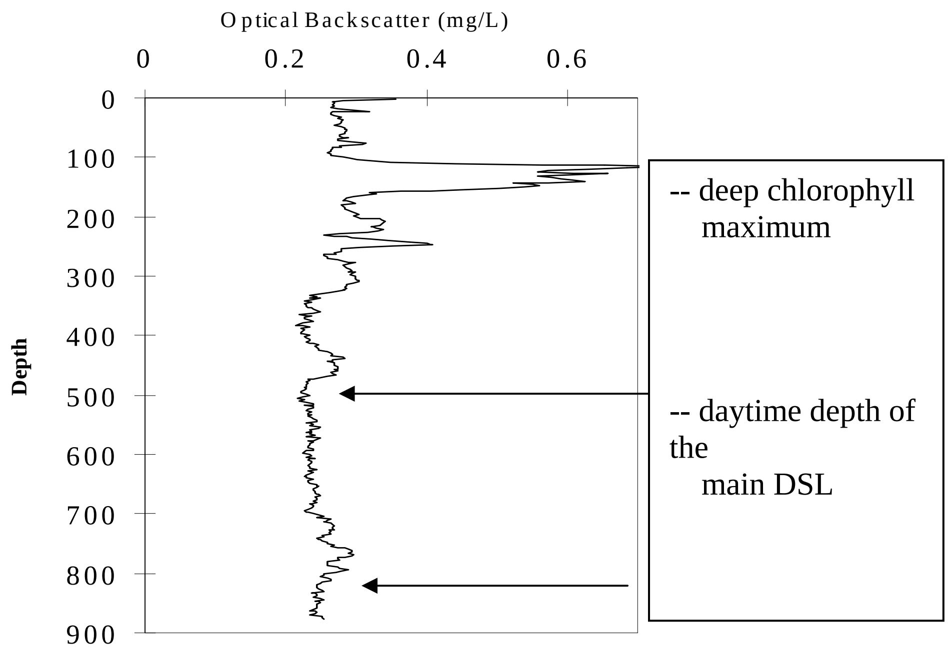


Figure 18. Station W3 optical backscatter profile taken during DGoMB 4B, summer 2000.

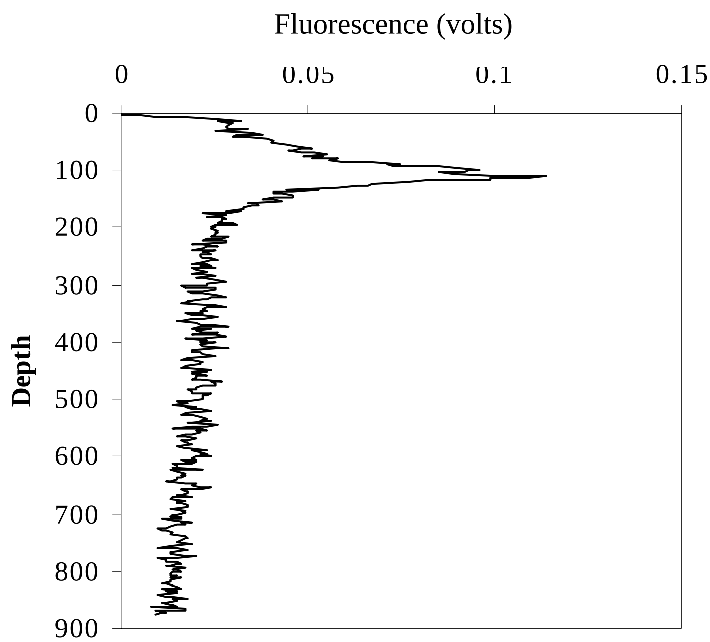


Figure 19. Station W3 relative fluorescence profile taken during DGoMB 4B, summer 2000. Chlorophyll maximum is represented by the large peak at 100m.

ADCP records. Other smaller peaks in OBS from 200 to 350 meters and from 700 to 800 meters are not associated with fluorescence peaks, and may represent concentrations of organic aggregates or other materials of heterotrophic activity. Figure 20 shows the location of where the OBS profile was made over the continental slope. Other OBS and fluorescence profiles in deep water from the central basin were usually lacking secondary peaks in the signal below the main DSL.

Analysis of hydrographic influences

Sea surface height anomalies detected by satellite altimetry documented large variations in eddy dynamics between cruises and between different regions within cruises (Figure 21). The presence-absence comparison of secondary DSLs, found secondary DSLs present at the targeted depth (>650 meters) 1/3 of the time while in a cyclone, 3/8 of the time in a confluence region between hydrographic features, and about 1/2 of the time in the area away from eddy influence (Table 5). However, a secondary DSL was only detected once out of 4 periods while in the anticyclone. Figure 22 shows the deep water backscatter as a time-series plot over the entire cruise from 600 to 700 meters, showing very little low frequency variability. This may suggest that deep layers are less influenced by surface circulation features.

The Spearman Rank correlation is a non-parametric statistic that gives a descriptive index of agreement between ranks of individuals. The Spearman Rank correlation (r_s) was preformed for one-day average backscatter profiles from cyclonic versus anticyclonic regions at the targeted depth range for the secondary DSL

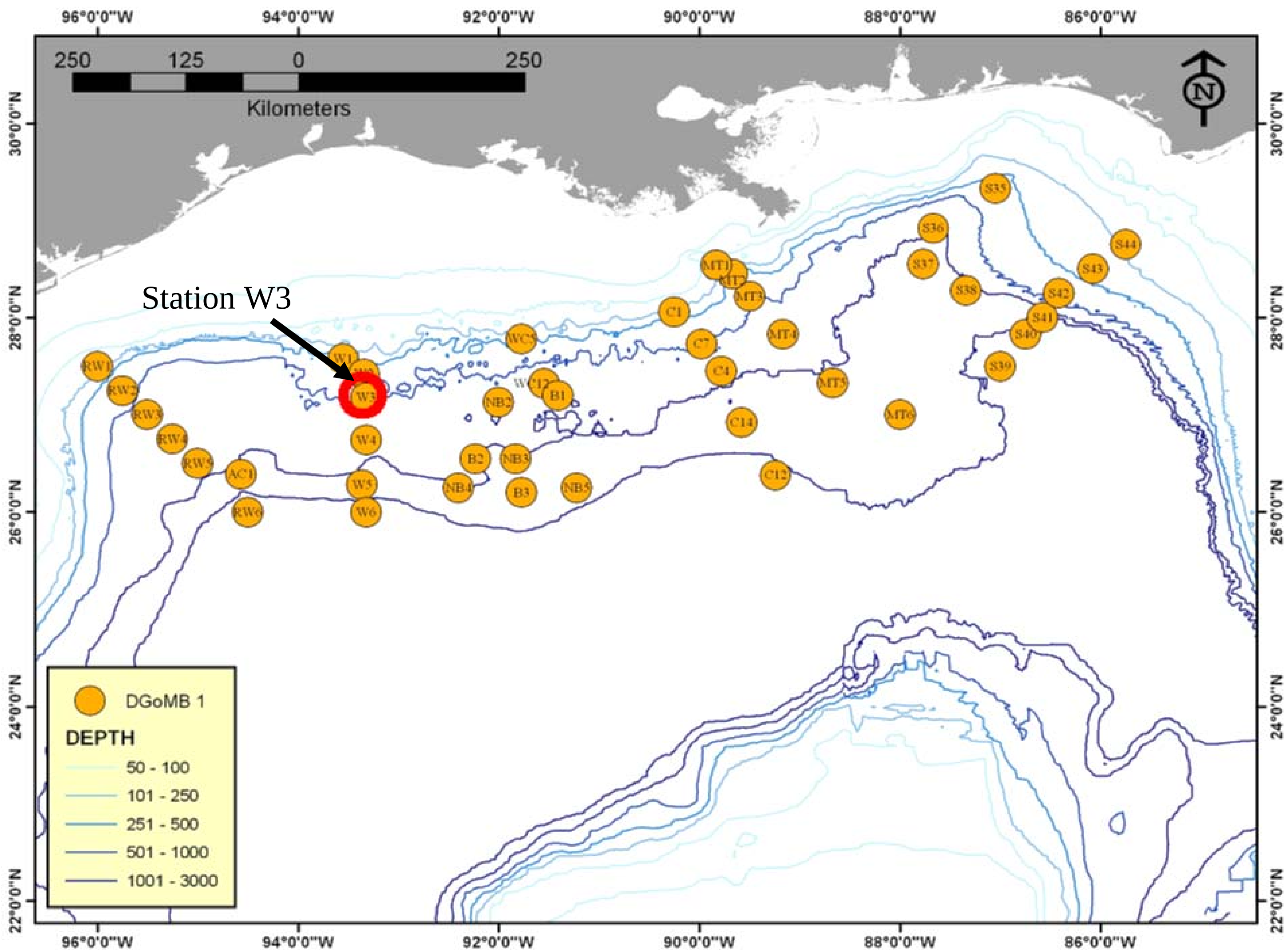
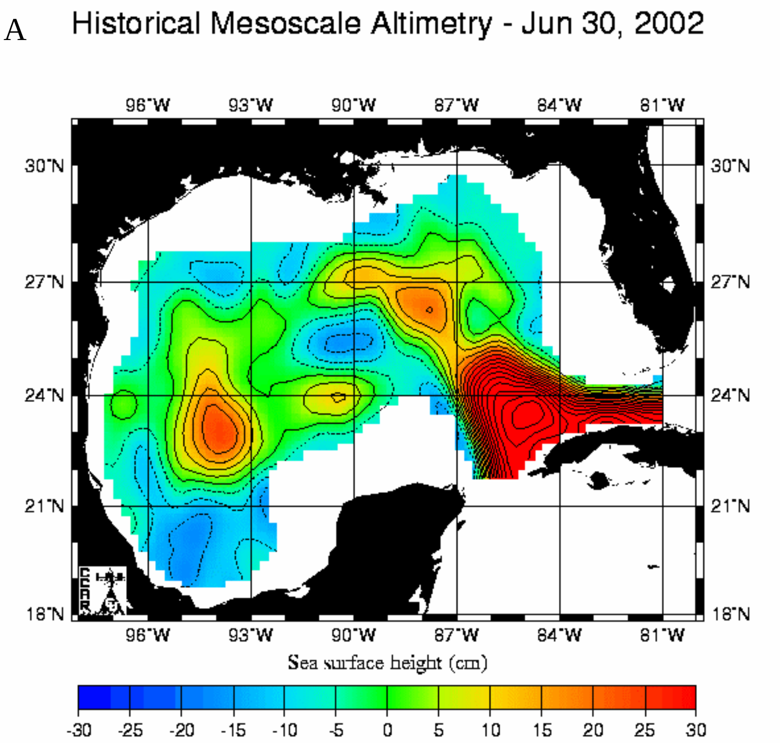


Figure 20. Gulf of Mexico map of DGoMB stations, occupied in summer 2000. The circled red station illustrates the location of the CTD at station W3, in the northwestern Gulf of Mexico slope, which provided optical backscatter and fluorescence data.

A



B

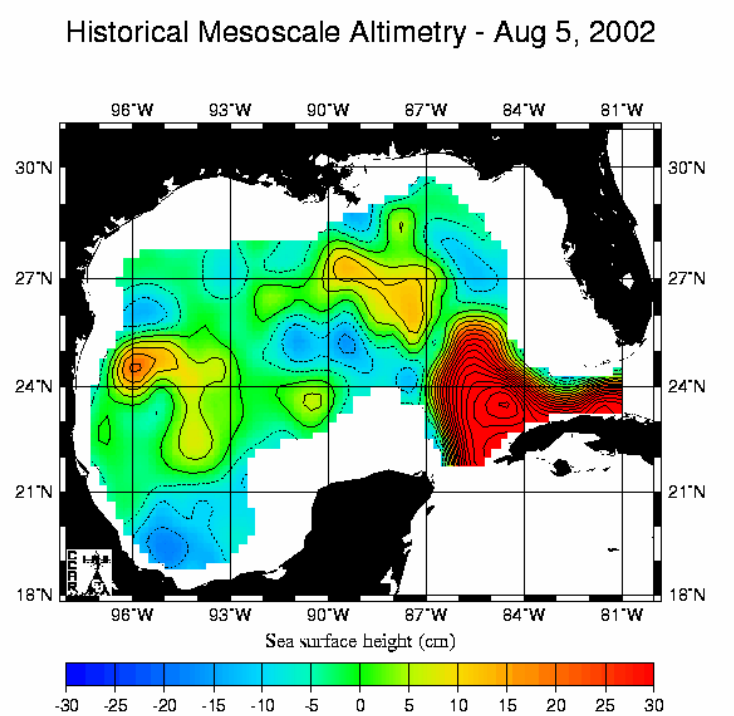
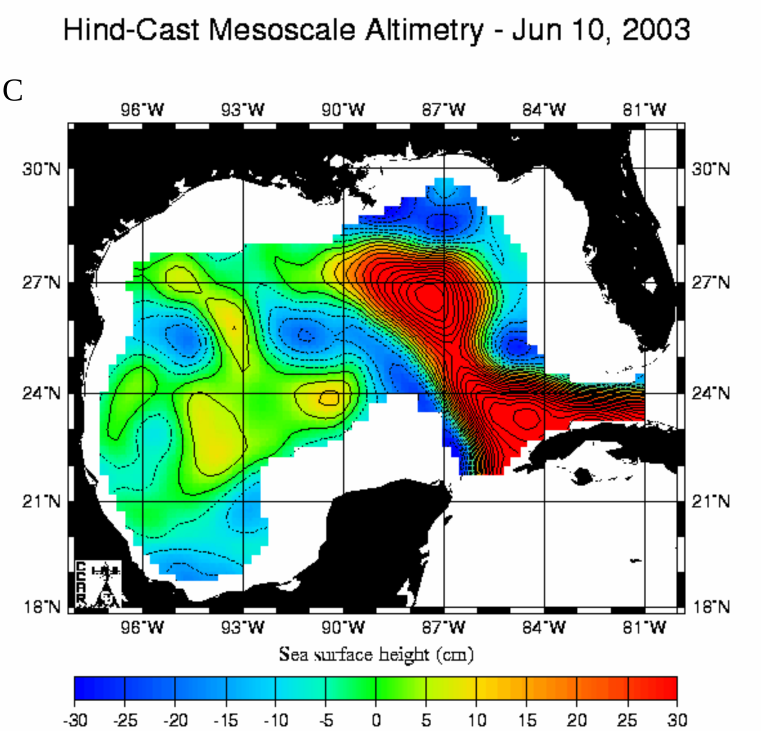


Figure 21. Satellite altimetry maps of sea surface height taken mid-cruise for each of the 4 SWSS cruises on the *R/V Gyre* from 2002 to 2003. A) 2002 s-tag; B) 2002 d-tag; C) 2003 habitat survey; D) 2003 s-tag. Sea surface height images from CCAR (http://ccar.colorado.edu/~realtime/gsfc_gom-real-time_ssh/).

C



D

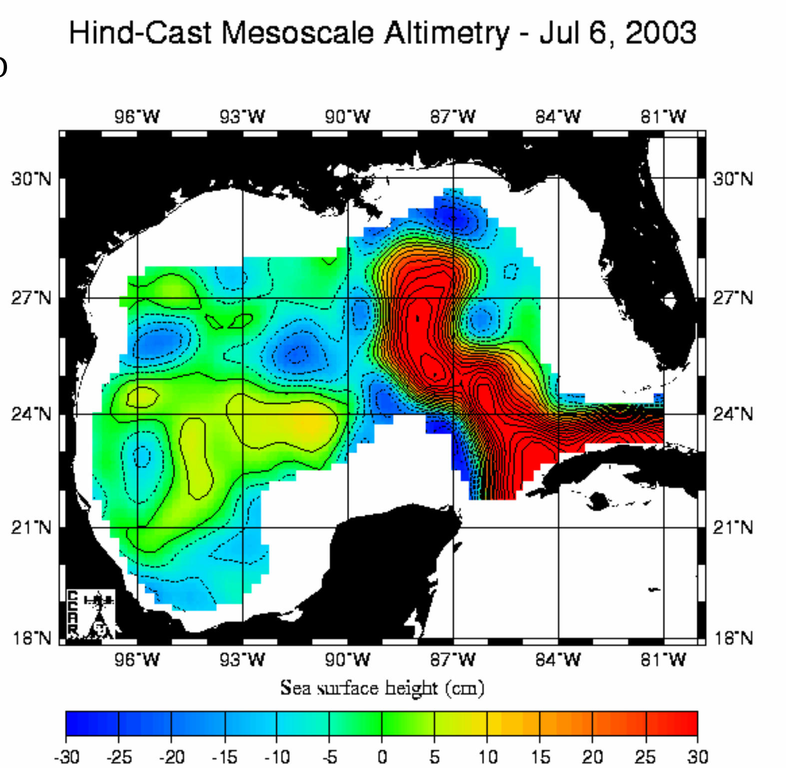


Figure 21 Cont.

Table 5
A secondary DSL at the targeted depth range was observed 1/3 of the days in a cyclonic feature, 1/4 of the days in the anticyclone, 3/8 of the days in the confluence region, and 7/16 of the days spent in regions with no distinct circulation features present

Day in which there was a presence of a deep DSL (>650m) out of the number of possible days when in cyclone, anticyclone, boundary, or no hydrographic feature.

Cruise	**Cyclone**	**Anticyclone**	**Confluence**	**Other**
SWSS02 s-tag	0/1	0/1		3/8
SWSS03 hab	2/2	1/3	1/1	4/5
SWSS03 s-tag	0/3		2/7	0/3
TOTAL	2/6	1/4	3/8	7/16

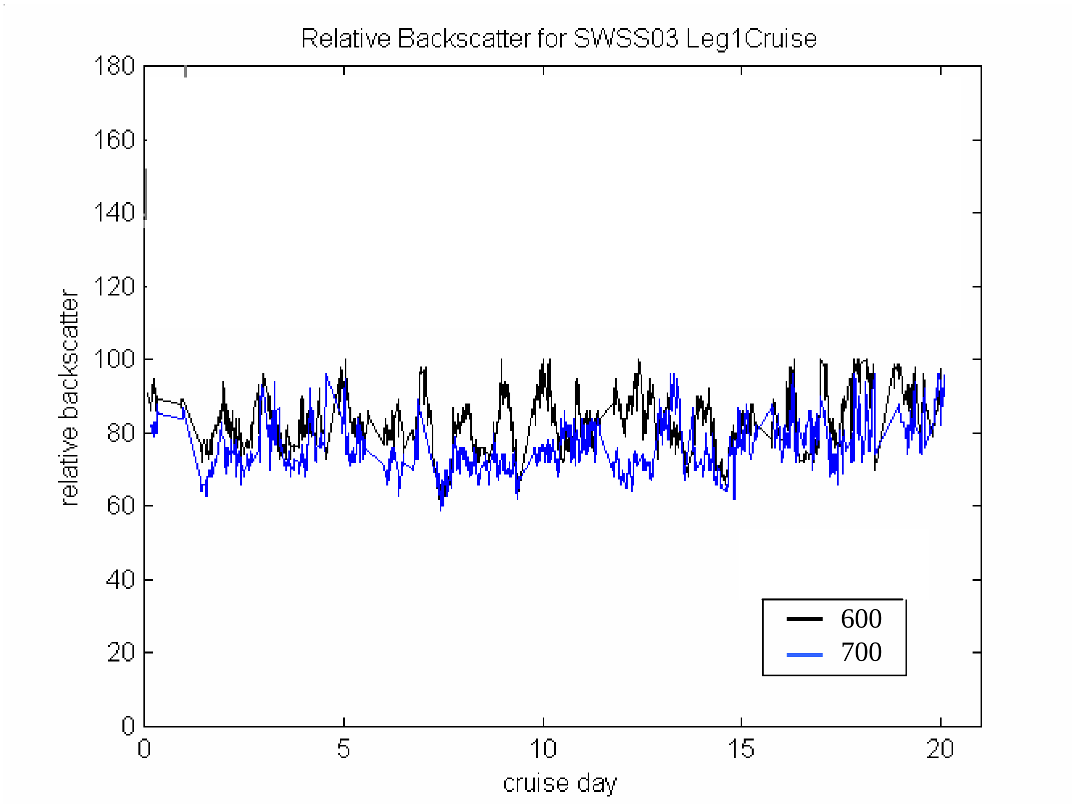


Figure 22. Time series of 38-kHz ADCP RABI at 600 and 700 meters during SWSS 2003 habitat and survey cruise. There was very little low frequency variability at these depths.

(650 to 800 meters). R_s between the cyclonic and anticyclonic average profiles did not show a significant difference between the 10 bins ($r_s = 0.93$), indicating that the ranking orders are very similar. Similarly, a two-tailed t-test did not show the average profiles were significantly different between 650 and 800 meters ($p=0.15$).

Because the presence-absence of secondary DSLs below 650 meters in the various hydrographic regions suggested these were less common in anticyclones, specific days of work in anticyclones during each of the cruises were looked at in more detail. In addition to the SSH or 15°C depth, the overall size and strength of anticyclonic eddies and their locations in the Gulf of Mexico basin likely also play a role on the amount that they influence the DSL. During the SWSS03 habitat cruise, a very pronounced anticyclone Loop Current eddy (LCE), 'Eddy Sargassum', extended unusually far north to the northern slope of the Gulf of Mexico (Jochens and Biggs, 2004). Although the cruise track of the ship never reached the center of this anticyclone, the ship surveyed along the northern edge of Eddy Sargassum on June 8, 2003. The daily ADCP backscatter record on June 8 had no detectable secondary DSL. By the 15th of June, the ship had worked its way north and east, into a cyclone over the slope. The ADCP backscatter from this day shows a large amount of backscattering below 600 meters.

Towed hydrophone arrays, which recorded acoustic detections of sperm whales throughout the cruise, showed that sperm whales were not present in the anticyclonic LCE (Figure 23), although they were frequently annotated in the cyclone to the northeast. The ship track of the SWSS 2002 cruise traversed a much smaller anticyclone feature on June 23, 2002. Although it was in a region characterized by SSH as anticyclonic, there was a secondary DSL present between 650 and 700 meters, and the acoustic survey for sperm whales detected several whales along the 1000 meter isobath south of the Mississippi River delta (Figure 24). Compared to the 2003 cruise during a strong Loop Current eddy and an area of DSL and sperm whale absence, the 2002 anticyclone was weak and not associated with the absence of secondary DSLs or sperm whale acoustic detections.

IKMT net trawling

Although trawling during the SWSS habitat survey cruise was not designed for sea-truthing of the ADCP, the trawls did provide some useful insights into deep-living water column fauna (see Table 6). Trawl samples were first quick-sorted into 3 categorizes of crustaceans, cephalopods, and hatchet fish for later taxonomic sorting. While several different variables may be influencing the volume of organisms caught, the greatest rank order factor in determining the volume of trawl catch appeared to be the trawl depth. Figure 25 shows that the deepest trawls tended to have the smallest catches while the shallowest trawls averaged the highest catch. Comparisons of trawl catch volume with the 38-kHz ADCP backscatter signal did not, however, show a distinct relationship. The problem with such comparisons, is that without the sound attenuation coefficients for the instrument, RABI from different depths can be compared only as relative rather than absolute intensity to compare with the trawl samples collected.

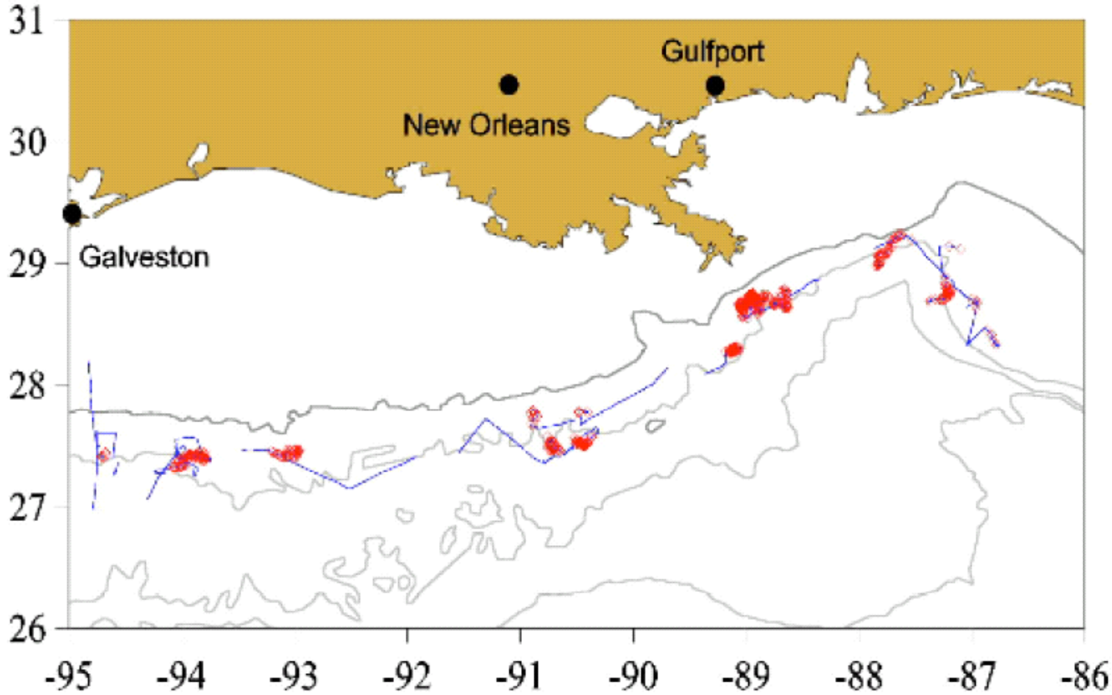


Figure 23. Acoustic detections of sperm whales (shown in red) on SWSS03 Leg1 cruise, superimposed on cruise track occupied while towing hydrophone arrays (blue lines). Isobaths shown are 200m, 1000m, 2000m, and 3000m. Figure from Jochens and Biggs, 2004 in SWSS year 2 annual report.

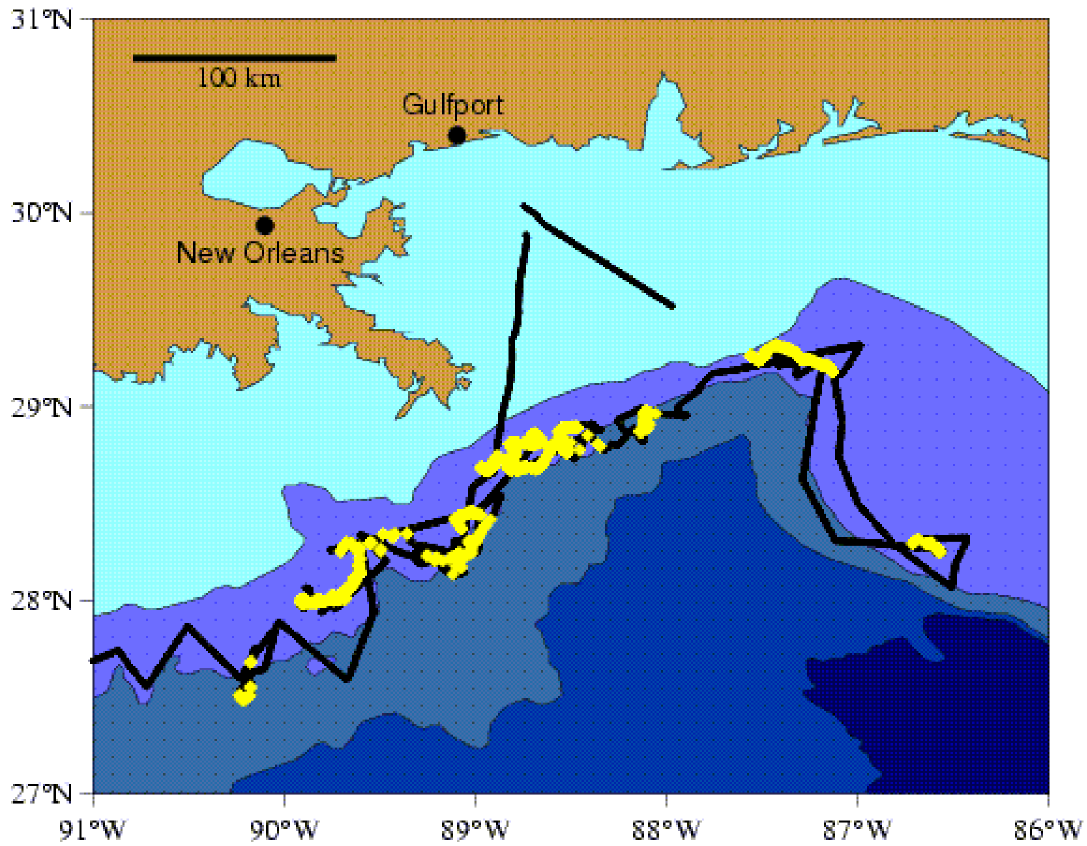


Figure 24. Acoustic detections of sperm whales (yellow squares) shown along the cruise track during the SWSS s-tag cruise, 2002. Whales were detected along the southern Mississippi River delta. Depth contours shown are 200m, 1000m, 2000m, and 3000m. Figure from Jochens and Biggs, 2003 in SWSS year 1 annual report.

Table 6
Taxonomic classification of all crustaceans, cephalopods, and hatchet fishes caught in 23 IKMT net trawls taken during SWSS trawling on cruise 03G06. Data provided by John Wormuth (TAMU)

Crustaceans

Oplophoridae
Acanthephyra acanthitelsonsis
Acanthephyra acutifrons
Acanthephyra curtirostris
Acanthephyra gracilipes
Acanthephyra purpurea
Hymenodora gracilis
Janicella spinicauda
Meningodora mollis
Meningodora vesca
Notostomus elegans
Notostomus gibbosus
Oplophorus gracilirostris
Oplophorus spinosus
Systellapsis cristata
Systellaspsis debilis
Systellaspsis stylorostriatus

Pasiphaeidae
Parapasiphae sulcatifrons
Pasiphaea merriami

Pandalidae
Parapandalus richardi
Parapandalus willisi
Plesionika grandis
Plesionika polycanthomerus

Mysidacea
Lophograstridae
Gnathophausia ingens
Anomura

Euphausiacea
Bentheuphausia amblyops
Euphausia brevis
Euphausia gibboides
Euphausia mutica
Euphausia pseudogibba
Euphausia similis
Euphausia tenera
Nematobrachion boopis
Nematobrachion flexipes
Nematobrachion sexspinosus
Nematoscelis atlantis
Thysanopoda aequalis
Nematoscelis gracilis
Stylocheiron maximum
Thysanopoda acutifrons
Thysanopoda cristata
Thysanopoda egregia
Thysanopoda monocantha
Thysanopoda obtusifrons
Thysanopoda orientalis
Thysanopoda pectinata
Thysanopoda tricuspidata

Penaeidea
Funchalia villosa
Gennadas bouvieri
Gennadas bouvieri
Gennadas capensis
Gennadas valens
Sergia challengeri
Sergia grandis
Sergia robustus
Sergia splendens
Sergia tenuiremis
Sergestes corniculum
Sergestes alanticus
Sergestes sargassi
Sergestes vigilax

Cephalopods
Abralia atlantica
Abralia redfieldi
Abralia veranyi
Abraliopsis pfefferi
Abraliopsis sp.
Bathyteuthis abyssicola
Brachioteuthis sp.
Chiroteuthidae
Chiroteuthis sp.
Cranchiidae
Enoploteuthidae unidentified
Galaiteuthis sp.
Haliphron mollis
Helicocranchia papillata
Heteroteuthis sp.
Histioteuthis arcturi
Lycoteuthis springeri
Octopoteuthis neilseni
Octopod unidentified
Ommastrephidae
Ornithoteuthis antillarum
Pterygioteuthis gemmata
Pterygioteuthis giardi
Pterygioteuthis sp.
Pyroteuthis margaritifera
Sandalops sp.
Pyroteuthidae
Stenoteuthis pteropus

Hatchet Fish
Argyropelecus aculeatus
Argyropelecus affinis
Argyropelecus gigas
Argyropelecus hemigymnus
Argyropelecus sladeni
Sternoptyx diaphana
Sternoptyx pseudobscura
Polyipnus clarus

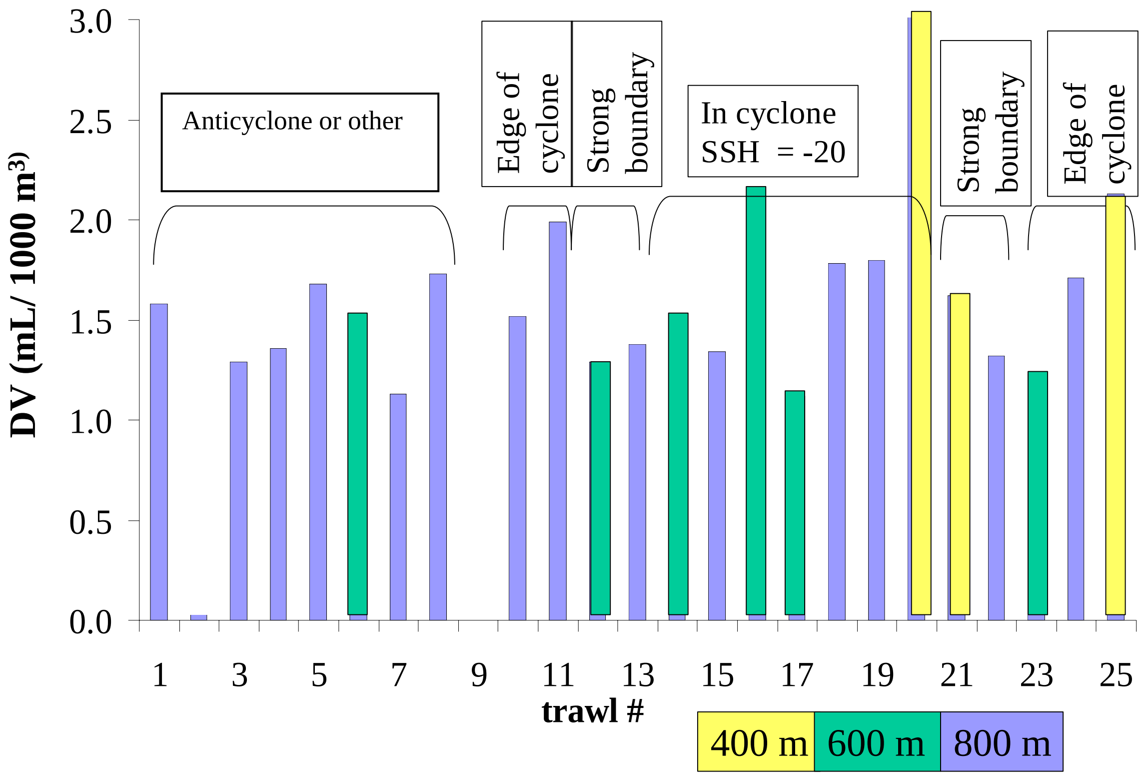


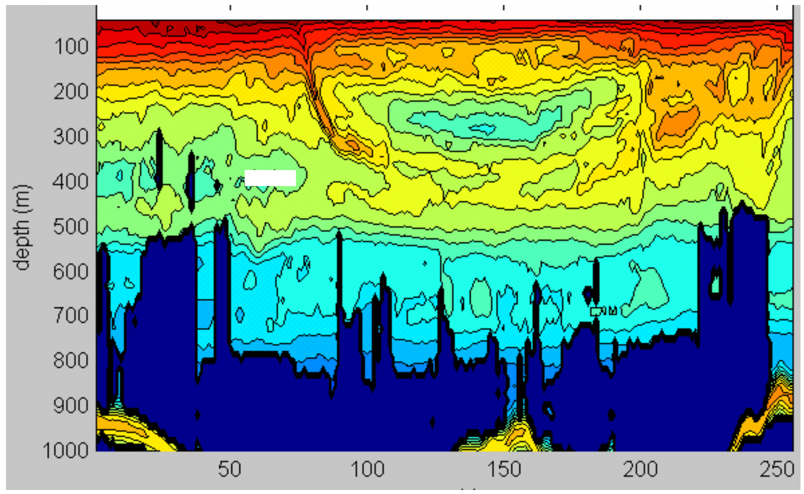
Figure 25. Total wet displacement volumes of IKMT collections during SWSS03 habitat survey cruise (May 31 - June 21, 2003). Trawls were targeted for 400, 600, and 800 meters, the general circulation regime is displayed above the trawls. Trawl 2 was an anomalous low trawl and 9 sample was lost.

Fish were the most abundant group in the trawls, and displacement volumes of the total fish catch in trawls targeted to 400 meters averaged greater than in trawls targeted to deeper bins. Since trawls were done at night, the vertical migrating organisms were at the surface and so shallow trawls would spend proportionally more time in or near the surface scattering layer. Trawl 20, which was targeted to catch fish in the upper 400 meters, had the largest total displacement volume (4.52 mL/1000m^3). When the time and depth of this trawl was plotted over the 38-kHz ADCP backscatter, it revealed that the trawl was in an area of relatively high acoustic backscatter associated with the DSL (Figure 26). This trawl 20 also took place in a cyclonic region (SSH = -25cm). In contrast the trawl 3, which reached a maximum depth to 685 meters, had a total displacement volume of just 1.29 mL/1000m^3, or roughly one fourth caught in trawl 20. Trawl 3 was also in a general anticyclonic region (SSH = 10cm). In summary, the proximity to the DSL and whether the trawl was fished in or out of an anticyclone likely had an influence on the biomass in the trawling depths. The deepest trawling depth reached by the net was probably the strongest influence on the total catch.

Discussion

Traditionally, studies involving cetacean ecology have focused on their distributions determined by visual and acoustic detection surveys. Griffin (1999), however, argues that a refined understanding of cetacean and other apex predator distributions from an ecosystem or community viewpoint is needed. The DSL can be seen as one of the trophic steps between primary producers and the ultimate apex

<u>Trawl 20</u>
max trawl depth = 359m
water depth = 1000
15º depth = 170m
SSH = -25cm
DSL BS = 150
total DV = 4.52



<u>Trawl 3</u>
max trawl depth = 685m
water depth = 850m
15º depth = 230m
SSH = 10cm
DSL BS = 105
total DV = 1.29

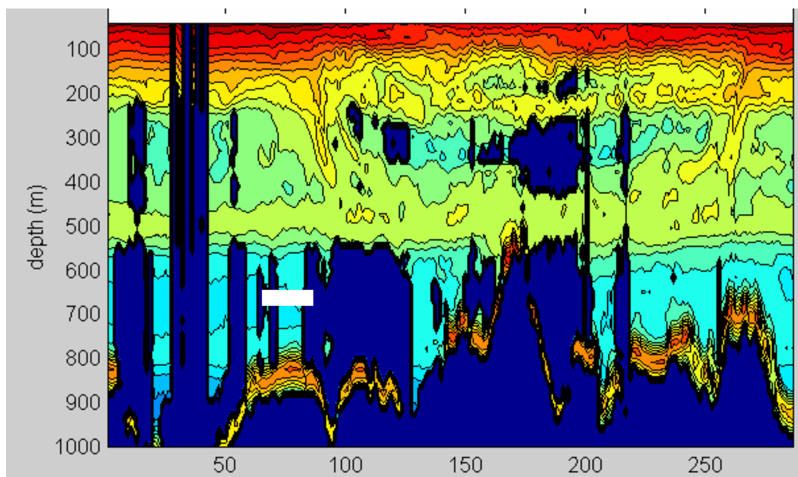


Figure 26. Two examples showing the targeted trawl depths (white) plotted over the 38-kHz ADCP RABI running plots. For all trawls, many variables both physical and biological likely influence the standing stock of biomass. No single variable examined provided a clear correlation with the trawl displacement volumes and the acoustic backscatter signal.

predators, the sperm whales. First, phytoplankton production is the basis for the zooplankton abundance that the animals in the DSL feed on. Secondly, DSL animals including euphausiids, crustaceans, small fish and small squid, provide prey for the large squid that sperm whales directly feed on. This ecosystem is dynamic, i.e., changes in the distribution and abundance at any one of these levels will likely result in a related response in the other levels. However, this response does not necessarily mean a direct and immediate effect. For example, there is believed to be a weeks-to-months time lag between a phytoplankton bloom and the associated changes in zooplankton and fish production. As a corollary, the absence of squid and DSL prey is believed to result in the sperm whales temporarily relocating to another region where prey is more abundant (Jaquet and Gendron, 2002).

Squid, the main prey for sperm whales, are ecological opportunists and their abundance can fluctuate widely between generations, making them a difficult group to predict recruitment in variable environments (Rodhouse, 2001). Their variability also makes it difficult for sperm whales to expect where to find squid, and so, whales tend to travel large distances over a short time while foraging. However, if squid depend on prey in DSLs, we can use acoustic survey data showing the presence or absence of DSLs to predict where squid, and consequently, sperm whales will most likely be found.

Foraging by apex predators is difficult to study since it occurs in such a vast and deep area. However, the D-tagging portion of SWSS has provided data revealing the depths of foraging and the diving behavior of the whales (Johnson and Tyack, 2003). A 2003 d-tag dive profile shows a whale which consistently dove to between 650 and 700 meters on repetitive dives, even though the bottom depth changed over that time. This provides evidence that the whale was feeding in or parallel to a layer that stays at the same depth, rather than following the bottom topography. We could expect that the dive profile would follow a similar pattern as the secondary DSL if it were to shoal to shallower depths, for example in areas where there is a decreased light extinction. Other predators clearly track diel changes in scattering layer depth. The predatory Atlantic redfish when observed acoustically followed the diel vertical migration of their euphausiid prey (Gauthier and Rose, 2002). The depth of foraging dives by Galapagos fur seals has also been shown to closely follow the cyclical variations of the depth of the DSL (Horning and Trillmich, 1999). Fur seals are visually cued to their prey, but were shown to forage at depths following the DSL response to the lunar light cycle.

The S-Tagging portion of SWSS has provided horizontal movements of sperm whales indicating preferential regional habitats likely in optimal feeding grounds. S-Tags are satellite tags that track the position of the whale (Mate and Krutzikowsky, 1995). Whales tagged in summer 2002 generally stayed in the same geographic area along the mid-slope of the northern Gulf of Mexico over the time being tracked, and others tagged in summer 2003 did the same (see Mate and Ortega, 2004 in Johchens and Biggs, 2004). The slope-deep basin 38-kHz ADCP RABI comparison on the presence of secondary DSLs between 600 to 700 meters showed that such DSLs are more common over the slope than in the deep basin. This is probably due to the closer proximity to nutrient rich coastal water and the frequent occurrence of cyclone eddies and confluence zones which lead to high chlorophyll concentrations and attracts many foraging animals.

In contrast, the deep basin of the central Gulf of Mexico is most frequently associated with the anticyclonic Loop Current blue water and low chlorophyll.

Traditional methods for squid stock assessments have generally been conducted by net trawling techniques and population estimates based on jigging catch per time effort. Both of these techniques have associated biases. Low catch numbers and high variability of a large cephalopod trawl catch data set suggests problems with the sampling techniques used, primarily net avoidance (Wormuth and Roper, 1983). Net avoidance is the major factor leading to underestimates of the squid population. On the other hand, squid are often attracted to lights used during fishing, leading to over-estimates.

There is increasing interest in acoustic surveying methods. Because of their composition, squid are relatively weak acoustic targets, which makes them hard to detect. Using a Simrad EK500 echosounder at 38 and 120 kHz with simultaneous net trawls, Goss et al. (2001) demonstrated that squid detection from 80 to 300 meters below the surface is possible despite their weak target strength. Future surveys attempting to acoustically estimate squid biomass should focus their attention to methods similar to those used by Goss that can distinguish signals of animal types based on the various target strengths.

Deep scattering layers are an important trophic link between plankton and sperm whales. Studies on the DSL and vertical migration are important to characterize the habitat of sperm whales, because it seems intuitive that the amount of prey in the DSL should have a direct effect on sperm whale feeding. The presence and the intensity of the secondary DSL in deep water (650 to 800 meters) was shown to be different between the middle slope and the deep basin, and also some differences were observed between anticyclone features and all other circulation features that coincided with temporary sperm whale sightings during the SWSS cruise. This study has suggested there is a connection between plankton in the surface waters and sperm whales, via the diel vertical migrations of the main DSL, although there appears to be no direct link. Future studies are needed to further understand the trophic links associated with the DSL, squid, and sperm whales.

CHAPTER V

SUMMARY AND CONCLUSIONS

Since scattering layers in the Gulf of Mexico likely include prey animals for higher trophic levels, understanding of their patterns of abundance and distribution is important when focusing research at any of the tropic levels involved. This research found that different variables may play a notable role in determining the presence, intensity, and depth of the DSL. A major change in the daytime depth of the main DSL was observed near a large river plume, believed to be caused by the shoaling of scatterers because of decreased light penetration in surface waters. Changes were also observed in the relative strength of the main DSL that appeared to be due to mesoscale eddy circulation influences. The influence of the small changes in sea surface height that are associated with periodic cyclonic and anticyclonic eddies can have an enormous impact on the biology in the Gulf of Mexico.

In addition to the regional and hydrographic variability of the main DSL, this research also provided important descriptions of the diel vertical migrations undertaken by the animals of the DSL. The 38-ADCP demonstrated a method of calculating vertical migration rates and migration timings much easier than the traditional methods that used multiple net trawling.

This was the first ADCP study in the Gulf of Mexico that focused on a secondary DSL located below the main scattering layer. This was valuable for the habitat characterization of the sperm whales, which have historically been extremely difficult to make any direct correlations with their prey. Although the 38-kHz ADCP probably can not resolve the large squid prey directly, it likely was able to image aggregations of the probable prey of squid. Such deep-living scatterers should be more closely trophic linked to sperm whales than some of the previous oceanographic characterization studies of epipelagic plankton and micronekton that used ADCP data from higher frequencies.

In conclusion, there is a great potential for future related work. Unlike the diel vertically migrating organisms of the DSL, the faunal community below the main DSL has not been well studied. This study provided the first acoustic backscatter data with secondary DSLs as a main focus. The 38-kHz ADCP proved useful in relative spatial comparisons of backscatter. Although limited to comparisons based on relative changes of the signal at one depth because the absorption coefficient was unknown, the backscatter data were beneficial for studying the presence and absence locations of the secondary DSL at the depth sperm whales dive to. Once backscatter from this instrument can be used on an absolute scale, we will then be able to quantify each scattering layer compared to layers at different depths, and also relate the biomass within the main daytime DSL relative to the biomass within deeper DSLs and in the surface layer.

Experimental calibration of the ADCP to obtain both a beam spreading factor and the absorption coefficient is required for the conversion to absolute backscatter. Optimally, this calibration would require precise long range positioning of a target with known acoustic scattering characteristics in clear water. Methods for doing this have been suggested as positioning the target and ADCP suspended in deep clear-blue water below the scattering layers and where there would be very few scatterers interfering. Suspending the experiment in deep water eliminates ship noise, surface reflections, and interference from biological scatterers and layers. The target and ADCP could be in the same horizontal plane orientated towards each other rather than orientated vertically in order to simplify the experiment. A horizontal orientation should eliminate any confounds from overlying scattering layers, but horizontal spatial variability of scatterers is likely to contribute to the variability.

Another major direction for future work related to this study would be to focus on the secondary scattering layers in the depth range of sperm whale diving using a different acoustic source that could directly resolve individual large squid and fish targets (Benoit-Bird and Au, 2001). This could be achieved with a multiple-frequency towed echosounder like Biomapper (Wiebe et al., 1996). Towed echosounders like this have been used in GLOBEC fieldwork, to allow different groups of targets to be distinguished based on their target strength. If squid generally have a different target strength than bony fish and crustaceans, then individual targets might be identified based on their target strength characteristics

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RESEARCH INTERESTS

- Acoustic surveys of scattering organisms and prey layers
- Physical forcing on biological processes
- Cetacean behavior and habitat characterization

PRESENTATIONS

- "38-kHz ADCP investigation of Gulf of Mexico deep scattering layers."
  Poster presentation given at the American Geophysical Union Ocean Sciences Meeting, in Application of Acoustics to Oceanography, session OS51E. Portland, OR, January, 2004.